OPPORTUNITIES FOR ACADEMIC RESEARCH IN A LOW-GRAVITY ENVIRONMENT

Edited by
G. Hazelrigg and J. Reynolds

Progress in Astronautics and Aeronautics

Martin Summerfield

Series Editor-in-Chief

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Preface

A period of rapid advance in science or engineering tends to follow the development of a new theory or a new experimental method. For example, development of the wave theory of light led to a new understanding of the elemental composition of the universe, development of the optical microscope led to a new understanding of the mechanisms that cause disease, and development of the technique of gene splicing is leading to a new understanding of the functions and mechanisms of DNA. New experimental methods include not only procedures but also new environments in which research can be conducted. Space is such an environment.

The space environment provides unique characteristics for the conduct of scientific and engineering research. Extreme vacuums, down to 10^{-15} Torr, can be produced. Large experimental apparatus can be built and operated in space. There is no significant atmosphere to interfere with astronomical and other observation. Radiation unobstructed by the Earth's atmosphere can be studied scientifically and can be utilized for various purposes. Ultra-high speeds are possible above the atmosphere for long durations and can be the basis of novel investigations. And nearly gravity-free environments can be obtained. Each of these characteristics enables the conduct of a special set of experiments or measurements not otherwise possible. This book addresses those experiments and measurements that might become possible by taking advantage of low-gravity environments obtained in space.

Access to a low-gravity environment offers the possibility of improving the research process in the following three ways:

1) Better results may be obtained in certain projects if they are conducted in a low-gravity environment. For example, fluid flow and heat-transfer science might benefit from research in low and variable gravitational fields where the effects of gravity can be separated from other phenomena present.

2) Some projects may be able to obtain comparable results at a reduced cost. For example, the separation and purification of biological substances for detailed study on Earth may benefit from a low-gravity environment, making it possible to produce useful quantities at reasonable cost.

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3) New areas of research may open up to investigation, for example, testing various theories of gravitation and performing experiments on second-order or cooperative phase transitions.

The National Aeronautics and Space Administration (NASA) of the USA developed the Space Shuttle as the principal component of the national Space Transportation System (STS) and is proposing to construct an orbiting space station over the next decade. Other nations have announced similar plans for space laboratories. These and other elements of space infrastructure will enable many new activities to be conducted in space, especially research. As new space platforms such as longer duration space shuttles, the space station, and special free-flying platforms become operational, opportunities for fundamental academic research will greatly expand.

To explore the opportunities for research in a low-gravity environment, the National Science Foundation (NSF) conducted a one-and-one-half-day workshop entitled "Opportunities for Academic Research in a Low-Gravity Environment." The workshop was held in Washington, D.C., on July 10 and 11, 1985. It consisted of a series of formal presentations on eight topics, as defined below, followed by a panel discussion on the policy implications of the identified research opportunities. The papers prepared for this workshop are the basis of this book.

Topic 1: Infrastructures for Low-Gravity Research

Facilities enabling the conduct of research in low-gravity environments have expanded considerably over the past few years with the emerging operational capabilities of the Space Shuttle. It is now possible to place experimental apparatus in space, provide for their operation by man, and retrieve all or part of the apparatus for later analysis on Earth. These capabilities and facilities are leading to new areas of research in the physical sciences and engineering. This chapter discusses the emerging infrastructures for low-gravity research and the provisions that NASA has made for their exploitation.

Topic 2: Critical Phenomena

The study of critical phenomena is an important area of physics. Kenneth Wilson of Cornell University was recently awarded the Nobel Prize for theoretical work in renormalization theory. Experimental verification of his results are difficult, however, because of the nature of the materials involved. High-resolution measurements of critical phenomena, such as the lambda transition in helium—an example of a cooperative or second-order phase transition—are "rounded" by gravitational forces. By performing such measurements in a low-gravity environment, the transition points can

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be approached much more closely than they can on Earth. Two chapters in this area discuss very high-resolution measurements at low temperatures and critical point phenomena.

Topic 3: Gravitation

The development and testing of theories of gravitation is one of the most challenging areas of modern physics. Earth-based experiments are limited by many factors. The space environment, on the other hand, provides an opportunity to test relativity and other theories of gravitation. This chapter discusses the use of space to test the equivalence principle between gravitational and inertial mass.

Topic 4: Crystal Growth

The force of gravity interferes with the growth of several types of crystals, limiting the extent to which they can be grown on Earth. Recent experiments in space have demonstrated an ability to grow crystals up to 1000 times larger than comparable crystals grown on Earth, opening several areas for research. Techniques for growing crystals in space include melt growth, float zone growth, solution growth, and vapor growth. Crystal growth in space offers the prospect of growing large crystals for commercial use, instrumentation, and for research. Typical applications include electro-optical crystals and biological crystals (protein crystals), the latter being important in biotechnology research. This chapter discusses the opportunities for research in this broad field.

Topic 5: Metals and Alloys

Metals and alloys prepared on Earth are limited by the force of gravity, which, for example, may cause materials to separate on solidification. Preparation of materials in a low-gravity environment promises to extend material properties in many ways. For example, directionally aligned composites show potential for exceptionally high magnetic coercivity that could lead to order-of-magnitude increases in magnetic strength. Also, it may be possible to prepare miscibility gap alloys that defy preparation in a 1-*g* environment. This chapter reviews the prospects for metals and alloys research in a low-gravity environment.

Topic 6: Containerless Processing

Attempts to produce extremely pure materials on Earth are sometimes limited by contamination introduced by the containers in which the materials are produced. Elimination of such containers, as is theoretically possible in a low-gravity environment, could remove this limitation. This could lead to the production of amorphous materials that cannot be made on Earth. In addition, without the

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need for a container, measurements of molten material properties could be made at temperatures that exceed the melting point of crucibles. This chapter reviews levitation methods and discusses containerless research possible in a low-gravity environment.

Topic 7: Combustion

Theoretical constructs of combustion processes tend to ignore the force of gravity because of the mathematical complexity that it imposes. On the other hand, available experimental data have been acquired heretofore in a gravitational field on Earth or under conditions of acceleration. Attempts to include gravity in theoretical constructs tend to force the neglect of other effects; usually the inclusion of gravity requires truncation of the terms describing the chemistry of the combustion process. One purpose of performing combustion experiments in a low-gravity environment is to obtain experimental data that correspond to the commonly employed theoretical constructs. Experimental and theoretical findings derived from these data should serve as a basis for understanding combustion phenomena encountered under normal gravitational conditions. Combustion scientists have an even more pressing reason for seeking to understand the physical role played by gravity in all ignition and combustion phenomena; it is that only through such understanding can engineers develop confidence in coping with the ever-present fire hazard in space vehicles and space platforms. This chapter discusses combustion research in a low-gravity environment, including flame propagation and extinction, radiative ignition, and heterogeneous processes in autoignition.

Topic 8: Fluid Dynamics

The disciplines of fluid dynamics cover a wide range of topics that are researchable in a low-gravity environment. Three major areas include transport phenomena, large-scale fluid dynamic modeling, and surface-tension phenomena. The development of theories of transport phenomena are important for the development of equipment for separation and purification of such things as biological materials. Considerable progress already has been made in this area, with a promise of commercial products and materials for research becoming available over the next few years. Experiments in low gravity should enable verification of large-scale models of planetary circulations (atmospheres and oceans). Finally, low-gravity research should enable development of a fundamental theory of surface-tension-driven flows (Marangoni convection), important in the understanding of surface properties of liquid metals. Two chapters under this topic address low-gravity research in these areas.

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It was the intention of the Editors, in planning this book, to provide in a widely circulated form, a basis for innovative thought on research that might be performed in space laboratories in low-gravity or microgravity conditions. The preceding summary account of various scientific possibilities, which represents the scope of this book, does not represent, by any means, the wide range of scientific and engineering research that can be accomplished in a space laboratory. Thus, in the fundamental sciences alone, astronomers, biologists, physicists, and others in other disciplines have their own goals not mentioned here. This book is addressed mainly to research engineers and applied scientists, and even with this restriction, it represents only a sampling of topics. If new ideas for scientific research should emerge from the study of this book, it will have served its purpose.

We would like to thank Martha Pien of The MAXIMA Corporation, whose care and excellent editing brought greater lucidity to this book.

George A. Hazelrigg
Joseph M. Reynolds
August 1986

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Facilities and Programs for Research in a Low-Gravity Environment

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Historical Developments

Research in a low-gravity environment was initiated by NASA in the mid-to-late 1960s, fostered by the need to master propellant characteristics, fire control, and the assembly of structures in space--elements all essential to manned spaceflight. Propellant requirements of the Apollo lunar landing program stimulated research on the effects of surface tensions and inertia in partially filled containers. Similarly, interest in onorbit repair and assembly required engineering studies of brazing and welding phenomena under low-gravity conditions.

In the course of these investigations, it was found that unrestrained liquid masses would form large free-flying globules, that vapor bubbles could grow virtually without limit in boiling liquids, and that flames quickly become blanketed with their own combustion products. These effects of weightlessness were first treated as problems in the engineering of spacecraft systems, only later to be recognized as exploitable phenomena useful in creating novel processes and products in space.

In 1966, personnel from the NASA Marshall Space Flight Center embarked on a series of visits to manufacturing companies to explore possible industrial interest in space applications. In 1969, NASA initiated its first formal space processing activities under the Materials Science and Manufacturing in Space program. This program was jointly sponsored by the Agency's Office of Manned Spaceflight and Office of Aeronautics and Space Technology. To date, in-space materials processing research has been pursued

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on the Apollo, Skylab, and Apollo-Soyuz manned spaceflight programs, on sounding rockets, and most recently on the space shuttle.

Apollo

A materials-processing flight experiment program was inaugurated in 1971 when three demonstration experiments were performed on the Apollo 14 lunar mission. These simple science demonstrations consisted of heat-flow and convection, electrophoretic separation, and composite-casting experiments. On Apollo 16 in early 1972, a more ambitious electrophoresis experiment was conducted; also in 1972, Apollo 17 carried a heat-flow and convection demonstration.

Skylab

The 100-ton Skylab space laboratory station, flown during 1973 and 1974, offered the first opportunity for extensive experimentation in a low-gravity environment. A total of 15 materials-processing experiments and 9 science demonstrations were conducted on Skylab. The complement of experiments included crystal growth, metal composites, eutectics (a combination of two materials that has a lower melting point than either material alone), welding and brazing, fluid effects, and combustion processes.

A materials-processing facility was an integral part of Skylab and was designed to accommodate all Skylab space processing experiments involving the melting and resolidification of materials. This facility was capable of venting into space, thus providing an evacuated environment for the experiments desired. A multipurpose electric furnace capable of reaching 1000°C was fitted within the materials-processing facility, allowing eight metals experiments to be conducted.

Apollo-Soyuz

The joint Soviet-American Apollo-Soyuz Test Project (ASTP), which flew in 1975, carried 12 space processing experiments and three demonstrations, including crystal growth of semiconductors, zero-gravity processing of magnets, surface-tension-induced convection, density separation during solidification of two alloys, and halide eutectic growth. In addition, two electrophoresis experiments were conducted on ASTP, one of which was developed and funded by the Federal Republic of Germany.

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A modified Skylab furnace, capable of reaching 1150°C with increased control of temperature ranges, was carried aboard ASTP. ASTP allowed several investigators to confirm Skylab results and make additional tests of previously observed phenomena.

The Apollo, Skylab, and ASTP experiments were conceptually simple and limited in scope. The hardware was designed on the basis of equipment used on the ground and the experiments were supported by limited ground-based research. Consequently, the experiments were basically reproductions of current techniques of processing materials carried out under low-gravity conditions. With the close of the Apollo program in 1975, no further human-tended materials-processing research opportunities were available until the 1980s, when the space shuttle became available.

Ground-Based Facilities

Research in space tends to be complex, expensive, and time-consuming. Therefore, it is generally desirable that one undertake a space research project only after as much knowledge and experience has been gained through ground-based research as is practical to ensure that research conducted in space be as effective as possible. Low-gravity experiments can be conducted for limited periods of time using ground-based facilities, which have been developed both to gain new knowledge and to prepare experimenters for research in space. Low-gravity, ground-based research facilities include drop tubes, drop towers, microgravity research aircraft, and ground-based levitators. At one time, sounding rockets were also used to provide periods of low gravity--up to about 5 min--for research purposes; since the space shuttle has become available, however, the sounding rocket programs have been discontinued.

Drop Tubes

Four drop tubes, each of unique capabilities, are available for low-gravity research. Each is capable of accommodating small, uncontained material samples, which are to be heated to the melt phase and then allowed to resolidify under low-gravity conditions during free-fall in an evacuated tube. The drop tubes are located at the NASA Marshall Space Flight Center in Alabama and the Jet Propulsion Laboratory in California.

100-Meter Drop Tube. The 100-m drop tube in operation at NASA Marshall Space Flight Center is capable of

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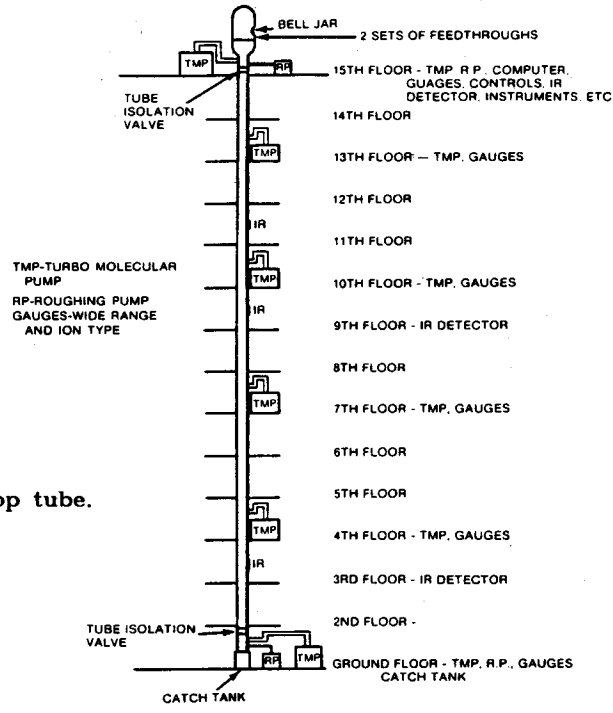

Fig. 1 The 100-m drop tube.

providing up to 4.6 s of low gravity. The facility includes three apparatus for melting samples over the range of 200°C to 3500°C (Fig. 1).

Electron Bombardment (EB) Furnace. The EB furnace operates between 1600°C and 3500°C and is used for experiments that are to be conducted in a vacuum environment. It uses the pendulant drop technique with omnidirectional electron bombardment for heating. The design of the furnace permits isothermal heating of samples with no more than a 25°C temperature gradient across a 5-mm sample at 2500°C. Heating power is controlled by regulation of the power supply or positioning of the sample. A viewing slit is provided through which the thermal history of luminous samples is recorded by an automated fast response (0.1 s) pyrometer. The emission current striking the sample can also be accurately recorded. The sample shape can be in the form of a wire, rod, or disc. Materials such as niobium, tungsten, tantalum, vanadium, platinum, and copper have been melted in the EB furnace.

Electromagnetic Levitator (EML) Furnace. The EML furnace operates between 500° and 3000°C and is used for experiments performed in vacuum and low-pressure

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gaseous environments. It is capable of levitating samples weighing up to .25 gram while allowing the sample to melt in a containerless state. Because it is a containerless-processing technique, crucible contamination is avoided when reactive metals are the subject of the experiment. The thermal history of the sample as it undergoes phase transition is recorded by pyrometer.

Resistance Heating (RH) Capillary Tube. The RH tube operates between 200°C and 1600°C and uses a quartz capillary crucible to contain the sample during melting. The tubing resembles an eye dropper, controlling the sample size by varying the orifice diameter and the pneumatic pressure used to eject the sample when melted. The sample is melted in an inert gas atmosphere to avoid surface reactions and contamination. The thermal history is recorded by thermocouples installed in the furnace. Spectral emissivity can also be recorded if necessary.

The drop-tube melting apparatus is housed in a stainless steel bell jar located directly above the stainless steel drop tube. The bell jar and tube are evacuated to a pressure of 10^{-6} Torr by six turbomolecular pumps located at equally spaced intervals along the tube. Acceleration of 10^{-6} g during cooling is attainable in the vacuum environment. The tube may be backfilled with inert gas to increase the cooling rate for low-melting-point materials, increasing the lowest attainable acceleration to 10^{-3} g in a helium (He) environment. Higher gas pressures--100 Torr to 750 Torr--can be used to increase cooling, although doing so results in substantial acceleration forces. Nonetheless, in this mode, the facility can be used for containerless processing.

Following free-fall, samples are decelerated and caught in a detachable fixture, which has a foil inner surface. As the sample is retrieved, dry nitrogen or argon gas can be used to prevent water vapor from entering the system.

Instrumentation and viewports are provided at three locations. Infrared detectors are mounted at each end of the tube and are used to determine the time of nucleation as the sample free-falls. The sensitivity of the infrared detectors is such that experiments with refractory metals of high melting point are most succussful.

30-Meter Drop Tube. The 30-m drop tube (Fig. 2) is also located at the Marshall Space Flight Center and is similar to the 100-m drop tube. Free-fall times in the 30-m tube are limited to 2.6 s. Heating apparatus available with the 30-m tube include the EB furnace and the RH capillary tube.

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13.7-Meter Force-Free Drop Tube. A 13.7-m, force-free drop tube is located at the Jet Propulsion Laboratory. This tube (Fig. 3) eliminates aerodynamic drag by forcing air downward with a 1-g acceleration by means of a suction fan mounted at the base. This acceleration is accomplished by tapering the drop tube to increase the air velocity as the air moves down the tube. The design of the tube contour includes a correction for turbulent wall boundary layer displacement and allows for selection of the gravitational force between 10^{-6} g and 1.0 g.

13.2-Meter Cryogenic Drop Tube. A 13.2 m long, 12.7 cm diam, thin-wall stainless steel drop tube, which provides 1.7 s of free-fall, is located at the Jet Propulsion Laboratory. Internal gas pressure can be controlled between 10^{-5} Torr and 30 psia. This tube (Fig. 4) provides three temperature zones. This first is near the melting or liquid temperature and provides for the symmetrization of the spherical sample. The second is cryogenic, where a liquid nitrogen cooling jacket cools the wall to cryogenic temperatures. The third zone is maintained at room temperature. Observation windows are located directly below the sample drop generator and in the lowest zone for visual sample access.

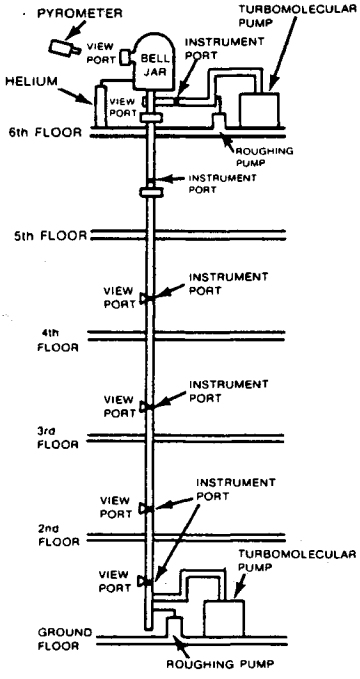

Fig. 2 The 30-m drop tube.

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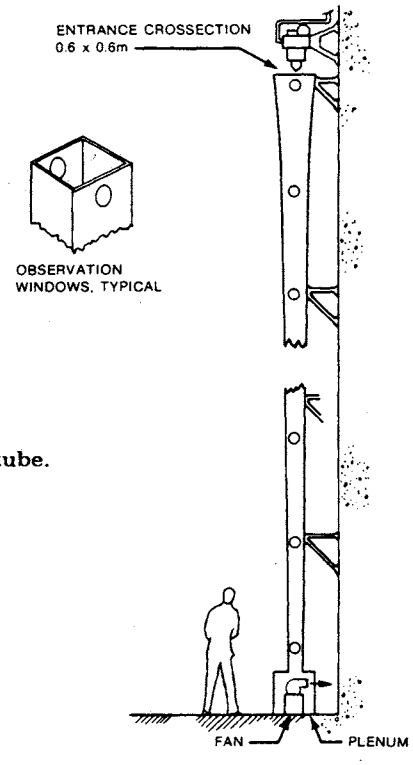

Fig. 3 The 13.7-m force-free drop tube.

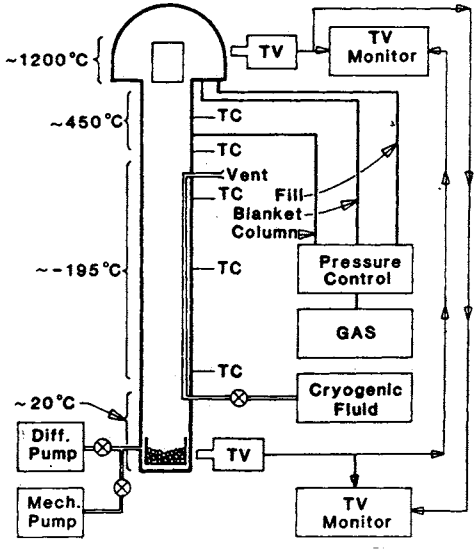

Fig. 4 The 13.2-m cryogenic drop tube.

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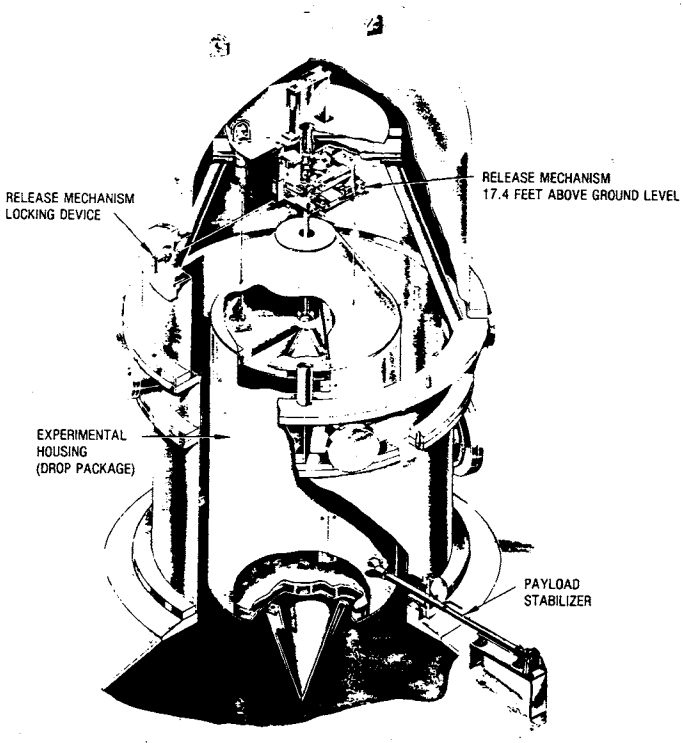

Fig. 5 Typical experiment capsule for the 145-m drop tower.

Drop Towers

Drop towers differ from drop tubes in their ability to accommodate large experimental packages, as opposed to small uncontained material samples. A drop tower usually uses a drop shield, which contains the experimental package and isolates the experiment from aerodynamic drag during free-fall. Auxilliary thrust may be provided to overcome the initial air resistance; however, facilities also exist that use an evacuated drop chamber.

Three drop towers are available. These are located at NASA Lewis Research Center in Cleveland, Ohio, and Marshall Space Flight Center in Alabama.

145-Meter Drop Tower with Vacuum Drop Chamber. A 145-m drop tower with integral vacuum chamber is located at the Lewis Research Center. The test chamber is a shaft lined with a 0.45 m to 0.60 m thick concrete casing, with an inside diameter of 8.7 m. The shaft extends 155 m, below grade elevation and contains a 6.1 m diam

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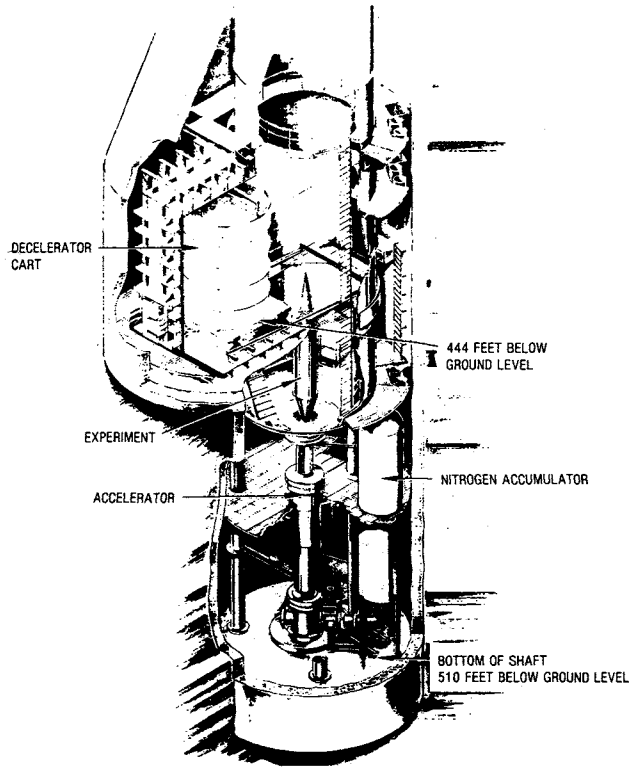

Fig. 6 Bottom of the 145-m drop tower.

Table 1 Specifications of the 145-m drop tower

Test facility performance	
Zero-gravity duration	Test Mode
5.15 s	Free-fall from top of vacuum chamber
10 s	Acceleration from bottom of vacuum chamber followed by free-fall
Deceleration rate	25 g mean with 35 to 50 g 20 millesec peaks
Vacuum test chamber	
Overall dimensions	6.1 m diam by 143 m deep
Drop height	132 m
Ultimate vacuum	10^{-2} Torr (in 1 h)

(cont.)

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Table 1 Specifications of the 145-m drop tower (cont.)

Deceleration tank	
Diameter	3.6 m
Depth	6.1 m
Service building	
South entrance	6.7 m wide by 7.3 m high rolling door (at assembly area)
Elevator	1360 kilogram capacity floor area 1.2 m x 1.8 m
Crane	18.14 metric ton capacity
Clean room	Fed. Std. 209 Class 10,000 (Class 100 potential)

Data Acquisition

18 channels of continuous data telemetered from experiment capsule (Standard IRIG FM/FM)
Frequency range: 6 cps. to 10,000 cps.
Overall system accuracy: 2-3 percent
High speed motion picture data: 500 frames/s, 1,000 quartz iodine lamps for lighting
High response tape recorder: 36 channels

Experiment capsule

Cylindrical vehicle:	
External dimensions:	1 m diam x 3.4 m high
Experiment volume:	1 m diam x 1.5 m high
Cold gas thruster for partial g acceleration of plus 0.003 g to 0.015 g	
Maximum payload weight:	453.6 kilograms
Rectangular capsule	
External dimensions:	5 m wide x 1.5 m long x 1.5 m high
Test specimen envelope:	4 m wide x .61 m long x .45 m high
Cold gas thrust systems:	0.003 g to .037 g positive acceleration 0.013 g to 0.07 g negative acceleration
Maximum payload weight:	69 kilograms
Sphere	
1 m diam x 2.5 c thick	
Maximum payload weight:	182 kilograms

Facility test frequency

One or two tests per day, depending on complexity of experiment

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vacuum chamber of 1.6 cm to 2.5 cm thick welded steel plates. A gravitational force of 10^{-5} g can be simulated by evacuation of the vacuum chamber to a pressure of 10^{-2} Torr. Low-gravity conditions can be achieved for 5 s to 10 s, depending on the acceleration obtained. Specifications of the 145-m drop tower are given in Table 1; cutaway views of the release station and bottom of the drop chamber are shown in Figs. 5 and 6.

100-Meter Drop Tower. A 100-m drop tower is located at the Marshall Space Flight Center. This facility, described in Table 2 and shown in Fig. 7, permits experimentation for up to 4.275 s, and can accommodate experimental packages up to 0.76 m^3 and 204 kilograms. The configuration includes a drag shield equipped with a battery, electrical distribution panel, and telemetry system. Auxiliary thrust is provided to overcome aerodynamic drag during the free-fall period.

30-Meter Drop Tower. A 30-m drop tower, shown in Fig. 8, is available at the Lewis Research Center. This facility achieves a low-gravity environment for up to 2.2 s. A drag shield is used to contain large experimental packages and to isolate the experiment from aerodynamic drag during unguided free-fall. The drag shield is decelerated in an 8-ft sand pit at the bottom of the tower. Battery packs are available for onboard power, and high-speed movie cameras are used to obtain a record of the experimental sequence. This tower has been used to assist graduate students in thesis research, with experiments having been conducted in combustion and fluid physics.

Table 2 Specifications of the 100-m drop tower

Total drop height:	101.7 m	Package size	
Free fall height:	8.9 m	Height:	.91 m
Drag shield free-fall time:	4.275 s	Width:	.91 m
Drag shield deceleration:	25 g	Length:	.91 m
Drag Shield Dimensions		Max Test Package Wt	
Length:	7.4 m	204 kilograms	
Diam:	2.2 m	Must be balanced	
Weight:	1642 kilograms		
Test area:	1.8 m x 2.4 m	Low Gravity Range	
		Max:	4×10^{-2}
		Min:	1×10^{-5}
		Aux Drag Shield Thrust: 35 kilograms	

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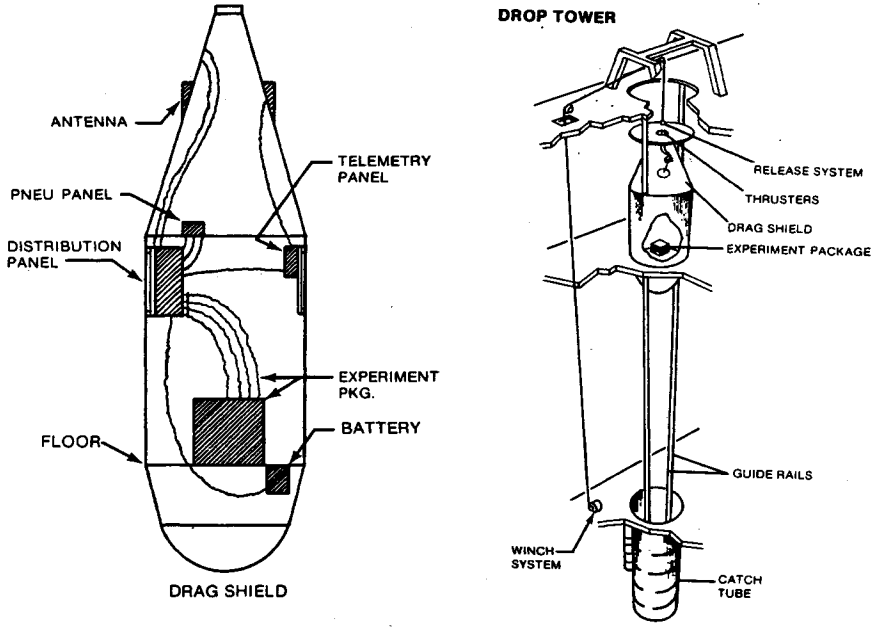

Fig. 7 100-m drop tower.

Low-Gravity Research Aircraft

Several aircraft have been used to simulate a low-gravity environment for up to 60 s. Three aircraft are currently in use by NASA.

F-104. The F-104 is a modified supersonic, two-place jet fighter (Fig. 9). Flying a parabolic trajectory between 25,000 ft and 65,000 ft, the F-104 is capable of a variable low-gravity period of approximately 60 s. The experimental package must be capable of surviving a 3-g acceleration and is restricted to a size of 10 in x 15 in x 21 in and a weight of 35 lbs. Experiments must be fully automated, except for on-off functions and are limited to one low-gravity maneuver per flight. The F-104 can provide 28 Vdc at 35 A and cooling air between 60°F and 90°F.

KC-135. The KC-135 is a four-engine cargo-type aircraft that can fly a 25 s parabolic arc between 24,000 ft and 34,000 ft (Fig 10). Up to 40 low-gravity maneuvers can be performed on a single flight. The experiment package must be capable of surviving 2.5-g acceleration. The KC-135 has a 10 ft x 54 ft cargo bay with an average overhead clearance of 6 ft and a maximum floor loading of

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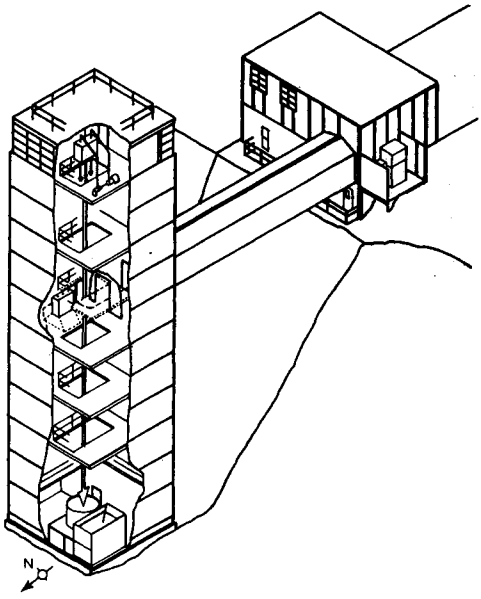

Fig. 8 30-m drop tower.

200 psf, allowing great flexibility in the size and weight of the experiment. Available power includes 28 Vdc at 80 A, 100 Vac at 50 A and 400 Hz, and 100 Vac at 25 A and 60 Hz.

Learjet. The Learjet Model 25 is a small executive jet capable of flying a parabolic trajectory between 11,000 ft and 18,000 ft and provides a low-gravity period of about 20 s (Fig. 11). Multiple low-gravity maneuvers can be flown on each flight.

Ground-Based Levitators

One application of a low-gravity environment is to facilitate containerless processing. Container walls produce nucleation sites, which alter the solidification process of metals and alloys. Without such nucleation sites, materials can be cooled well below their solidification temperatures while in the molten state. When solidification does occur, it proceeds rapidly in producing unique structures, sometimes with desirable properties such as high strength, resistance to corrosion, and magnetic "softness."

Levitation apparatus enable containerless processing in a low-gravity environment. In space, levitators can be used to position and manipulate samples during processing. A variety of force fields have been used to meet the

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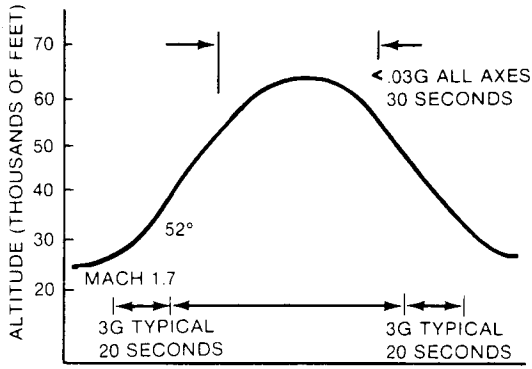
requirements of levitation for containerless processing. These include compressed air, acoustic, electromagnetic, and electrostatic techniques. Several levitation facilities are available for ground-based research.

Airjet Levitator with Carbon Dioxide Laser Heating. The airjet levitator uses a compressed air stream to levitate material samples for experiments in containerless-processing environments. During levitation, the samples can be melted with a 700 W carbon dioxide (CO_2) laser and then allowed to resolidify without physical contact with a containment vessel. Temperatures in excess of 2700°C have been obtained with this apparatus. The airjet levi-



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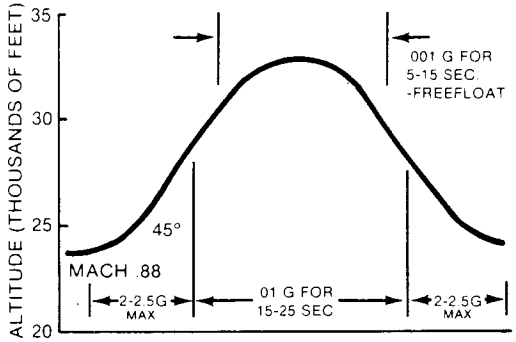
<.03G — 30 SEC.

Fig. 9 Flight characteristics of the F-104.



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<.001G—5.15 SEC.

Fig. 10 Flight characteristics of the KC-135.

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tator is located at the Marshall Space Flight Center and has been used principally in research on glass formation and oxide systems.

Electromagnetic Levitator with Electron Bombardment Heating. The electromagnetic levitator, located at the Marshall Space Flight Center, uses a 25-kW coil to produce a levitating magnetic field. This device also uses an auxiliary electron bombardment heating system and has been used to levitate and melt tungsten and other refractory metals. The facility includes a drop calorimeter for measurement of enthalpy of molten refractory metals.

Single-Axis Acoustic Levitation System. The single-axis acoustic levitation system (Fig. 12) is available at the Marshall Space Flight Center. This system consists of four major subsystems plus the necessary external control and support equipment. Central to the levitator is a furnace capable of operation at 1600°C, an acoustic subsystem providing levitation forces, a specimen control unit for insertion and retrieval of a test specimen, and a containment vessel to provide gas control and suitable pressurization. A test specimen can be inserted into the center of the furnace, released, and then positioned or levitated by the acoustic field. While levitated, the specimen can be melted and resolidified by cooling at a controlled rate.

Electrostatic Levitators. Three different types of electrostatic levitators have been successfully demonstrated at the Jet Propulsion Laboratory. These include a dish, ring, and tetrahedral levitator (Fig. 13). The first two

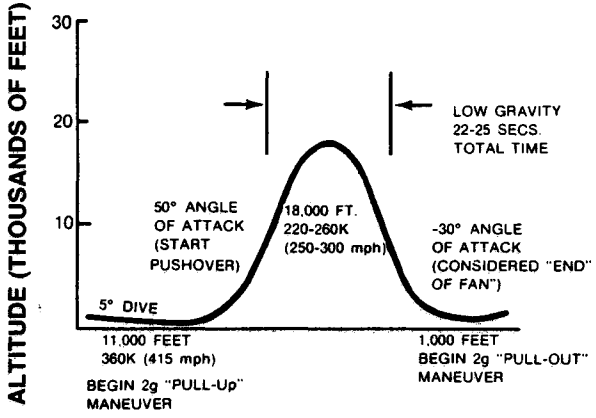

Fig. 11 Flight characteristics of the Learjet.

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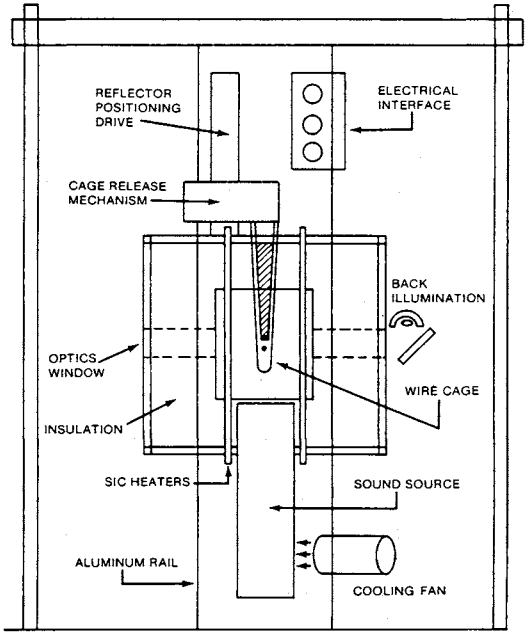

Fig. 12 Single-axis acoustic levitation system.

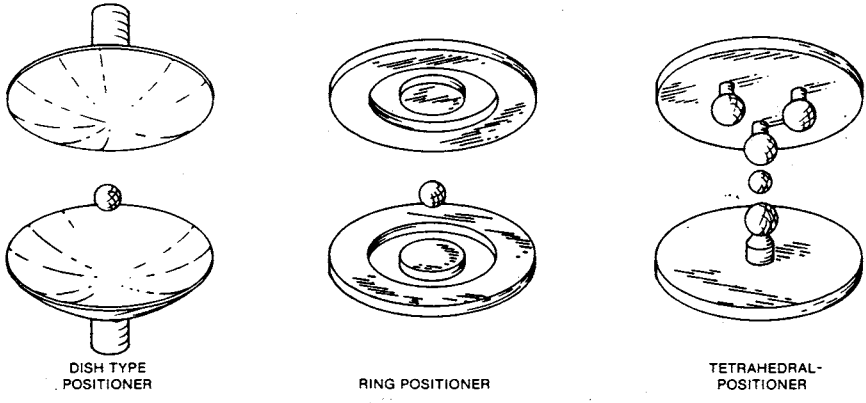

Fig. 13 Electrostatic levitators.

have axially symmetric shapes and have the drawback of only single-axis damping (the axis of symmetry). The tetrahedral levitator is capable of three-axis positioning and damping, which makes it particularly suitable for use in a low-gravity environment. Stable levitation of a glass shell 1.5 cm in diameter and 0.1 gram in mass has been demonstrated. In electrostatic levitators, the material is electrically charged and the force is produced by electric

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fields between electrodes. Stable positioning is obtained by a feedback system that constantly monitors the position of the object.

Space Shuttle Facilities

The growing operational capabilities of the space shuttle provide excellent opportunities for the conduct of research in a low-gravity environment. The space shuttle enables experiments to be conducted under conditions of relatively low gravity--on the order of 10^{-4} g continuously, down to 10^{-6} g for short periods of time--for up to about 7 days. These experiments may be human-tended and are returned to Earth for postflight evaluation and reflight. Research aboard the space shuttle can be conducted on the orbiter middeck, in the orbiter payload or cargo bay on specialized pallets, or in the pressurized Spacelab module.

The Orbiter Middeck

The orbiter middeck is a confined space located directly below the flight deck and adjacent to the payload bay. The orbiter middeck (Fig. 14) provides frequent access to a low-gravity environment for research purposes --three to five flight opportunities per year--along with simplified experimental payload integration (both in time and cost), access to the experimental equipment located on

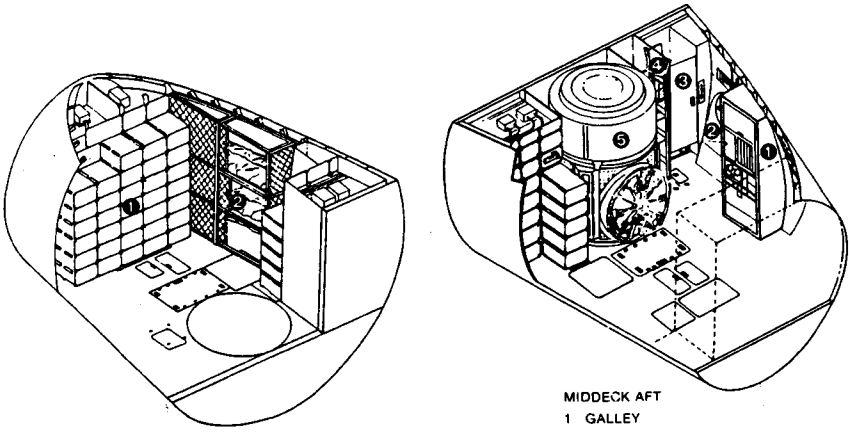

Fig. 14 Space shuttle orbiter middeck area.

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the middeck up to as late as 12 h prior to launch, and the possibility of crew interaction with the experimental apparatus. Middeck experiments are limited in size, power, and heat rejection. Operating temperatures are constrained to provide for crew safety and heat rejection, and power requirements are limited to 28 Vdc (up to 10 A) or 115 Vac (400 Hz, 3-phase, up to 3 A/phase). Standardized experiment carriers developed for use on the middeck include a series of large and small storage trays fitted to a modular storage locker and the Experiment Apparatus Container.

Modular Storage Locker. A total of 42 modular storage lockers are available in the middeck area. The standard lockers can be used with or without reusable trays. Eack locker provides 2 ft^3 of storage volume and is designed to hold 60 lbs maximum (40 lbs average for all lockers). The locker has a hinged door with a magnetic latch for onorbit use and two captive latches for securing the door during launch and entry/landing. The door has a friction hinge for low-gravity positioning and can be opened approximately 180 degrees.

Locker storage trays consist of pressure-formed plastic and are available in two sizes. Each locker is capable of receiving either one large tray or two small

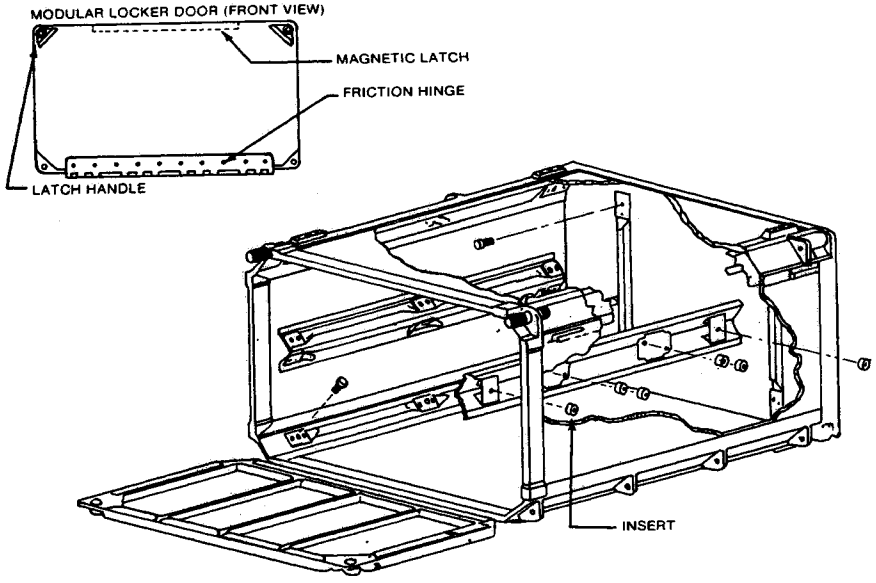

Fig. 15 Configuration of the Middle Storage Locker.

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trays. The large tray volume is 1.8 ft^3, with inside dimensions of 16.95 in x 20 x 9.59 in; the small tray volume is 0.85 ft^3, with the same length and width dimensions and a height of 4.64 in. The small trays are separated by guides containing friction devices on the locker sidewalls, allowing each tray to be removed individually yet keeping them in place in a low-gravity environment. The middeck locker (Fig. 15) can be replaced by the use of adapter plates, which are designed for attachment to the locker support structure in place of the lockers. Adapter plates are available in both single- and double-locker configurations and, along with modified locker doors, power cables, and connectors, can be provided as a part of the Middeck Payload Accomodation Kit (MPAK).

Experiment Apparatus Container (EAC). EACs have been designed for use in the middeck and payload bay. Their purpose is to contain experiments so that requirements for outgassing, flammability, and toxicity may be waived. The middeck EAC (Fig. 16) can include a Middeck Electronics Module (MEM) that becomes an integral part of the experiment, providing power and data acquisition/control elements. Both the EAC and MEM are configured for attachment to standard double and single adaptor plates and installation in the space provided for modular storage lockers. The maximum allowable weight of

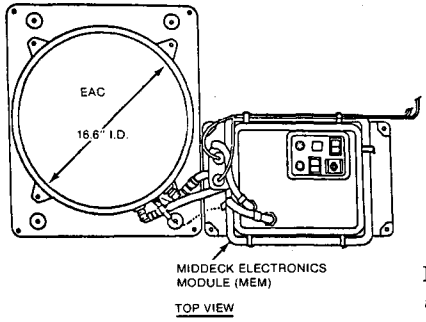
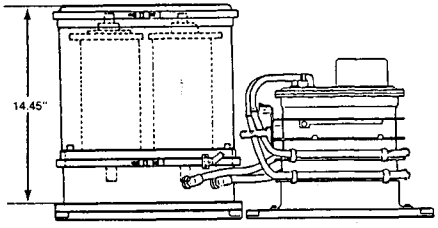


Fig. 16 The middeck experiment apparatus container.



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a complete EAC experimental package is 120 lbs. The EAC does not provide access to cooling in the locker area.

The Orbiter Payload Bay

The orbiter payload bay (Fig. 17) offers important advantages to certain experiments over the middeck area, such as higher operating temperatures, larger experimental volumes, and more massive experimental systems. These advantages come, however, at added integration time and cost, and forego the availability of crew interaction. Experiments in the payload bay are activated by remote control, with the exception of those experiments conducted in the Spacelab module. Carriers developed for use in the payload bay include the Materials Science Laboratory, the Materials Experiment Assembly, the payload Experiment Apparatus Container (EAC), and the Get-Away-Special Canister.

Materials Science Laboratory (MSL). The MSL is a multicapability research facility configured to carry a variety of experimental apparatus along with subsystems for data acquisition, system control, power distribution, and fluid handling. The base structure is referred to as a Mission Peculiar Experiment Support Structure (MPESS). Apparatus and subsystems are mounted on the MPESS to form a specific MSL configuration (see the MSL-2 shown in Fig. 18).

Similar in concept to the MSL is the Hitchhiker. This carrier also uses the MPESS base structure and a full

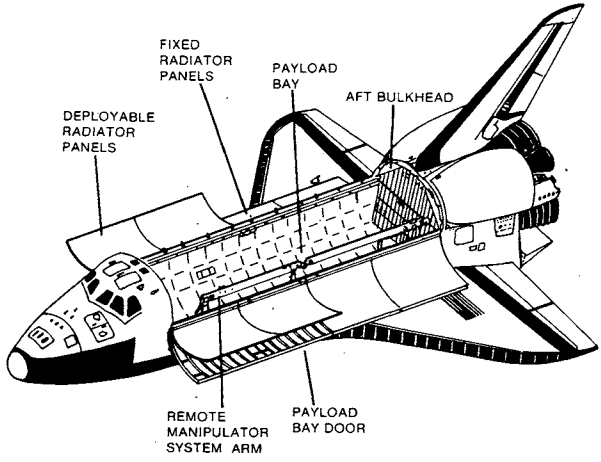

Fig. 17 Configuration of the space shuttle payload bay.

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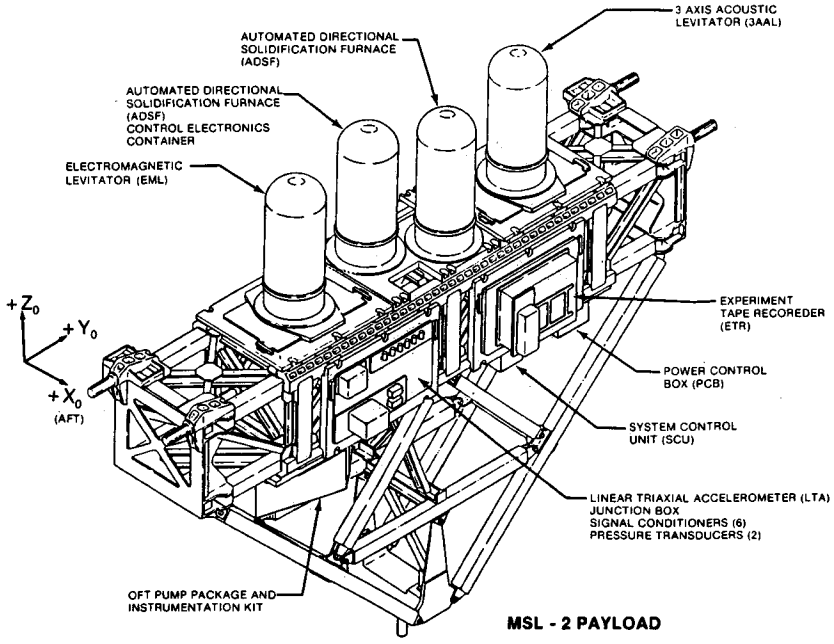

Fig. 18 The materials science laboratory.

range of host subsystems; however, the Hitchhiker will be used when additional payload bay capacity is available after manifesting of the primary payloads or when cancellations in the flight manifest result in available payload bay capacity. In essence, the Hitchhiker payloads fly "standby."

Materials Experiment Assembly (MEA). The MEA (Fig. 19) is similar in concept, but different in structure, to the MSL. It consists of a small group of up to three experimental apparatus integrated into one package and designed to be carried on the MPESS. The MEA contains specific experimental apparatus and subsystems integrated to form a unique MEA configuration. It typically comprises a small experiment system or group of small experiments that are completely self-contained and self-sufficient. Once a particular configuration is developed and proven flight ready, it may fly standby on a space-available basis with as short as a 6-month integration schedule.

Experiment Apparatus Container (EAC). The EAC designed for use in the payload bay is larger than the middeck EAC, although similar in concept, and it uses the

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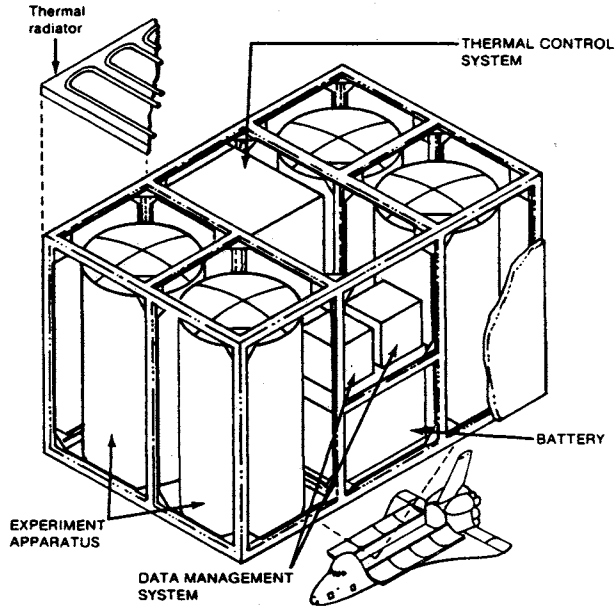

Fig. 19 The materials experiment assembly.

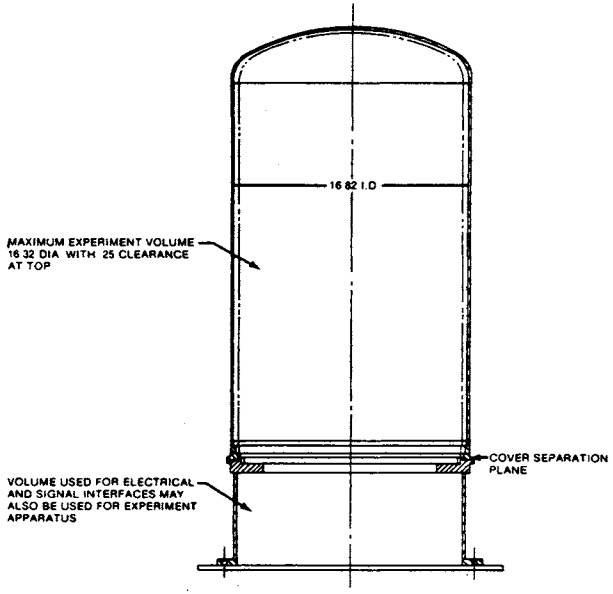
16 82 I.D
MAXIMUM EXPERIMENT VOLUME 16 32 DIA WITH 25 CLEARANCE AT TOP
COVER SEPARATION PLANE
VOLUME USED FOR ELECTRICAL AND SIGNAL INTERFACES MAY ALSO BE USED FOR EXPERIMENT APPARATUS

Fig. 20 The payload bay experiment apparatus container.

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MSL host subsystems for control and support (see Fig. 20). The EAC is suited to experiments with greater weight and power requirements than are available on the middeck.

Get-Away Special (GAS) Canister. The GAS canister is a standardized cylindrical aluminum container offered by NASA to experimenters for research in low-gravity science (Fig. 21). Standard canisters are provided in two sizes, 2.5 ft^3 and 5 ft^3, and will accept payloads of up to 100 lbs and 200 lbs, respectively. GAS canisters are designed to allow standard interfacing of small, self-contained payloads in the orbiter payload bay. They serve as pressure vessels, capable of evacuation and pressurization and include an insulated exterior on the bottom and side for thermal control. GAS payloads may use only three on-off controls operated by the shuttle crew. Electrical power, heating and cooling, and data acquisition must be provided with the experimental apparatus.

Spacelab

The Spacelab system was designed and built under the auspices of the European Space Agency (ESA) as a manned, low-gravity laboratory for flight in the payload bay of the space shuttle. Work on Spacelab commenced with a Memorandum of Understanding reached between ESA and NASA in 1973. Under this agreement, ESA assumed responsibility for design, development, construction, test, and delivery of a Spacelab engineering model, a Spacelab flight unit, spare parts, and two sets of Spacelab ground-

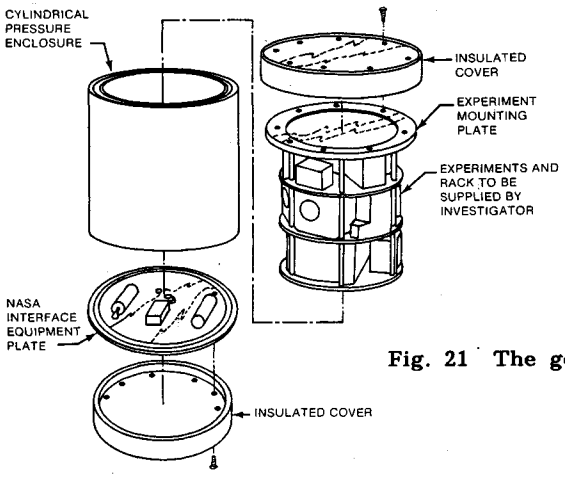

Fig. 21 The get-away-special canister.

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support equipment. Initial plans called for NASA procurement of additional Spacelab units, with ESA given the first chance at any follow-on production. Recently, however, the Spacelab program has been cut back to the existing Spacelab hardware and the procurement of a second unit.

The Spacelab system provides several modules that can be assembled into a variety of configurations for research in and on space. Provision is made for a near shirt-sleeve environment for onorbit human-tended research projects. Spacelab hardware includes cylindrical modules, pallets, an igloo, an instrument-pointing system, and the Spacelab tunnel (Fig. 22). Together they provide space and equipment mountings for experimental packages, electrical power (3-5 kW, up to 500 kWh), environmental control (4-6.6 kW heat rejection), data recording (30 Mbps digital) and transmission (50 Mbps digital downlink and 2 kbps uplink), and video downlink (4.5 MHz).

The cylindrical modules provide the pressurized environment for human-tended research. They consist of two segments: a core segment, including support systems for the modules and the pallets, and laboratory fixtures and working space; and the experiment segment, which is used to provide more working space with floor-mounted racks and benches. The core segment can be used alone if space requirements are modest, and the experiment segment can be added to the core segment if space requirements dictate. Each segment is 2.7 m long and 4.1 m diam. When attached, the combined length of the segments is 7 m. Each module has been designed with a reuse goal of 50 missions.

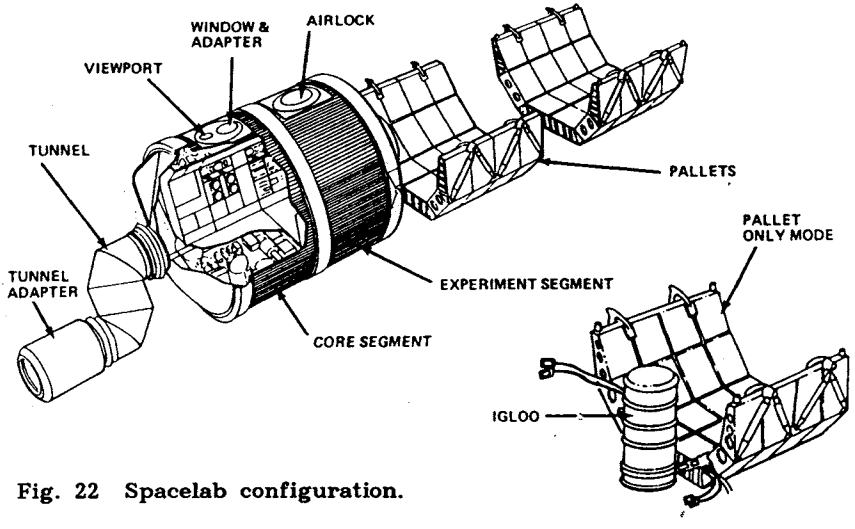

Fig. 22 Spacelab configuration.

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The pallets are open platforms that support instruments and experiments that require exposure to space. Each pallet segment is 3 m long, and five pallets are available for use. The pallets provide for instrument mounting and for the subsystems that cool equipment, furnish electrical connections, and furnish connections for experiment command and data acquisition. Each pallet can accommodate payloads up to 3,085 kilograms. When the Spacelab is used in the pallet-only configuration, the requisite subsystems, nominally contained in the core segment, are housed in a small, pressurized, temperature-controlled structure called an igloo.

The instrument-pointing system is a general purpose attitude-control system for pointing and controlling pallet-mounted experiments that require high pointing accuracy (1 arc/s). It can accommodate payloads of up to 2,690 kilograms, and it is 4 m long and 2 m diam. It includes a gyro unit and an electronics unit. The instrument-pointing system was designed to accommodate astronomy, solar physics, high energy astrophysics, and Earth-observation experiments.

The Spacelab tunnel is the adapter that provides a connection between the space shuttle and Spacelab core segment, enabling astronauts access and egress to the Spacelab. It is pressurized and segmented so that its length can be adapted to various needs, and it can be fitted with an airlock module that provides access to space.

Space Station

The space shuttle provides today for human presence in space and enables the conduct of experiments in a low-gravity environment for durations of about 7 days. The limitations on research in space imposed by the space shuttle will be largely removed when the space station, which will provide for human permanence in space, becomes operational in the 1990s. Great effort has already been devoted to space station planning to ensure its utility as a research laboratory.

The space station will include a manned multipurpose laboratory module uniquely suited to microgravity materials research. In preparation, the NASA Microgravity Science and Applications Program has initiated a study activity known as the Microgravity and Materials Processing Facility (MMPF). Design specification of the MMPF has already involved the academic and industrial communities through Discipline Working Groups and workshops, and through the space station Working Group, which works closely with the Space and Earth Sciences Advisory

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Committee (SESAC) Task Force on scientific uses of the space station. The SESAC Task Force is chaired by Dr. Peter Banks of Stanford University.

It is difficult at this time to identify the specific facilities and capabilities that the space station will include because these are still undergoing definition. But it is clear that a major focus of the space station will be the support of low-gravity research, and the organizations that will be in the best position to take advantage of the space station when it becomes operational are those organizations that will have been conducting low-gravity research prior to the availability of the space station, by using facilities such as the space shuttle.

Microgravity Science and Applications Program

Virtually all civilian research in a low-gravity environment is currently coordinated by the NASA Microgravity Science and Applications Program (see Appendix B). The goals of this program are as follows:

- To investigate the behavior of materials and fluids and the effects on processes carried out in the microgravity environment
- To provide a better understanding of the effects and limitations imposed by gravity in processes carried out on Earth
- To evolve processes that exploit the unique characteristics of the microgravity environment of space to accomplish results that cannot be obtained in unit gravity
- To explore and determine potential applications for the commercial use of space.

The Microgravity Science and Applications Program concentrates on the physical sciences but does not include the study of the effects of gravity on living organisms (research in this area is conducted under the auspices of the NASA Life Sciences Program). The current program includes the following six disciplines:

- Electronic materials
- Biotechnology
- Metals and alloys
- Glasses and ceramics
- Combustion science
- Fluid dynamics and transport phenomena

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Current supported research includes activities at approximately 60 universities, 10 industrial organizations, 3 nonprofit organizations, the National Bureau of Standards, 4 NASA Field Centers, and the Jet Propulsion Laboratory.

The Microgravity Science and Applications Program is divided into two elements: ground-based research and flight research. The ground-based research consists of laboratory research at the principal investigators' (PIs) home institutions and at NASA facilities, including drop tubes, drop towers, and aircraft, and at the Microgravity Materials Science Laboratory located at the NASA Lewis Research Center in Cleveland, Ohio. Ground-based research establishes the knowledge base and experience necessary for effective experimentation in space. The flight research element includes the apparatus development, PI support, and data analysis activities directly related to flight aboard the space shuttle. This program element includes experimental activities on the space shuttle mid-deck area, on specially designed support structures in the cargo bay, and in the pressurized Spacelab module.

One objective of the flight research element of the Microgravity Science and Applications Program is to construct and qualify space laboratory facilities that will support a range of experimental activities. During 1984, several apparatus were completed and readied for flight on the space shuttle. These apparatus include the following:

- Acoustic Containerless Experiment System (ACES)
- Isoelectric Focusing System (IEF)
- Automated Directional Solidification Furnace (ADSF)
- General Purpose Rocket Furnace-3 (Gradient) (GPRF-3)
- General Purpose Rocket Furnace-4 (Gradient) (GPRF-4)
- Electromagnetic Levitator (EML)
- Fluid Experiment System (FES)
- Vapor Crystal Growth System (VCGS)

During 1984, conceptual design reviews of proposed Physics and Chemistry Experiments (PACE) led to the approval of two flight programs. The first involves the measurement of the specific heat of He at the lambda point. The PI for this experiment is Dr. William Fairbank of Stanford University, who will be assisted by Dr. John Lipa. The second is on solid surface combustion with Dr. Robert Altenkirch of the University of Kentucky as PI. These research projects are described in later chapters of this book. Tentative approval for flight development was also

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given to the Advanced Automatic Directional Solidification Furnace (AADSF), designed to provide a broad range of materials-processing conditions. The AADSF will be used for the processing and growth of crystalline electronic materials such as mercury-cadmium-telluride (HgCdTe).

The Microgravity Science and Applications Program has established a series of reviews as standard for flight hardware development. These reviews ensure the consideration of all key aspects of each project while development is underway. Of foremost consideration is the continuing involvement of a science panel to validate that the hardware development is consistent with the approved science requirements. In addition, programmatic status is reviewed in detail to ensure adequate resources to effectively complete each project.

The following are synopses of low-gravity flight research activities undertaken to date.

Professor Harry Wiedemeier of Rensselaer Polytechnic Institute completed analysis of his vapor crystal growth experiment flown on the space shuttle flight STS-7, June 1983. Germanium-selenium (GeSe) crystals were grown by physical vapor transport in closed ampoules with a xenon buffer gas at 4 and 8 atmospheres with the use of the General Purpose Rocket Furnace (GPRF-2). The main objective of the experiment was to resolve the anomalous transport rates observed in GeSe growth experiments done on the Skylab and Apollo-Soyuz programs. The transport rates observed in Dr. Wiedemeier's experiment were within 20% of predicted rates and a factor of two lower than ground-control tests, confirming his theory that the prior anomalous rates were due to thermochemical effects of the homogenous gas-phase reactions. The experiment also achieved an unexpected result: some of the crystals grown in space were as large as 4 mm x 10 mm and 10 μm to 100 μm thick, as opposed to ground-control experiments that produced crystals no larger than 1-mm square. Additionally, the ground-grown crystallites showed numerous and irregular growth terraces with a swirl-like pattern suggestive of convective flow, as well as a high density of surface pits, the origin of which has not been identified. The space-grown crystals, in contrast, were extremely smooth with more regular and widely spaced growth terraces and showed no evidence of surface pitting. It has been concluded from these experiments that gravity-driven convection has a profound effect on surface morphology.

Flight experiments on STS-6 and STS-7 obtained data on continuous flow electrophoretic separation of biological substances. These data show the importance of different

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electrical properties; the electrical conductivity of the sample and the buffer solution must be carefully matched to avoid electrical field distortions and, thus, fully utilize the high sample concentration possible in low gravity. It was shown that dramatic increases in throughput can be realized in continuous flow electrophoresis performed in low gravity by increasing the flow channel width and the concentration of the sample stream. In addition, live kidney and pituitary cells were separated on STS-8. The objectives of this work were to isolate the subfractions of kidney cells that produce the largest amounts of urokinase (plasminogen activator) and to isolate the subfractions of rat pituitary cells that secrete the growth hormone, prolactin, and other hormones. Kidney cells were separated into more than 32 fractions in each of two electrophoretic runs. Multiple assay methods confirmed that all cultured kidney cell fractions produced some urokinase, and five or six fractions produced triple or more the urokinase than the other fractions. Several fractions also produced tissue-plasminogen activator. The pituitary cells were separated into 48 fractions, and the patterns of hormone distribution indicate that the in-flight control pituitary cells did not secrete nearly as much growth hormone into the maintenance medium as did the ground controls.

A monodisperse latex reactor (MLR) has been flown five times (on STS-3, STS-4, STS-6, STS-7, and STS-11) and has produced the first commercial material manufactured in space and marketed on Earth (Fig. 23). The

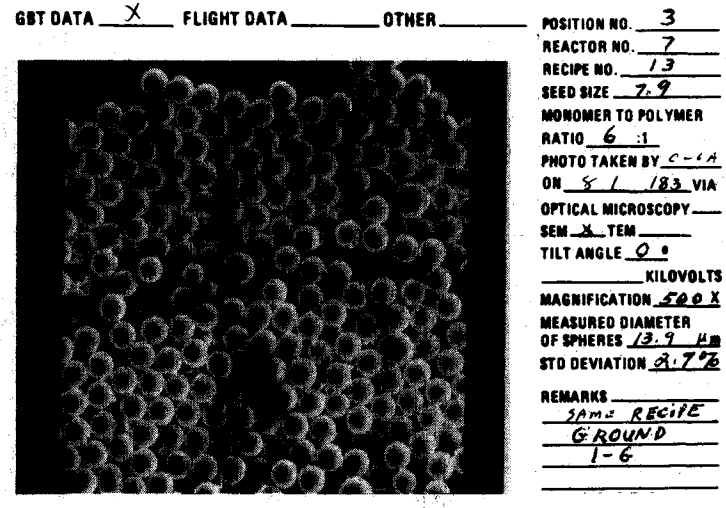

Fig. 23 Monodisperse latex spheres.

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National Bureau of Standards has approved and begun sale of 10-μm latex beads, manufactured on STS-6, as the U.S. national 10-μm standard reference material. The PI for this work is Dr. John Vanderhoff of Lehigh University. Larger monodisperse spheres, also produced in space, have several potential applications, such as drug carriers and tracers in the body, animal and human blood flow studies, membrane and pore sizing in the body, and medical diagnostic tests. They may also be used for optical and electron microscope calibration, Coulter counters, and light-scattering devices.

The ground-based research program comprises about 100 individual research tasks in six program discipline areas. The majority of these tasks are intended to lead directly to a flight project; the others are specifically intended to provide the mathematical and theoretical models against which low-gravity experimental results are analyzed and evaluated. The following are highlights of the ground-based program.

Electronic Materials

Dr. Klaus Bachman of North Carolina State University is conducting experiments in the II-VI materials, a family of compound semiconductors that can be lattice-matched for the growth of epitaxial HgCdTe. To develop more information on the growth of these materials, Dr. Bachman has grown crystals of CdTe, zinc-cadmium-telluride (ZnCdTe), manganese-cadmium-telluride (MnCdTe), and cadmium-selenium-telluride (CdSeTe) by the Bridgman technique. The CdTe crystals exhibit photoluminescence at room temperature, which implies that the crystal quality is very good. Photoluminescence measurements on the ZnCdTe show the deep level as being compositionally dependent, but a constant distance from the band edge. That is, as the zinc content is increased, the band gap increases and the energy level of the deep level increases at the same rate. The deep level also exists in the CdSeTe. Further studies of these materials are planned to determine the cause of the deep level and to explain its unusual dependency on the various materials parameters.

Ground-based tests for the effects of convection on crystal homogeneity and morphology are continuing. A technique for electrochemically etching lead-tin-telluride has been developed. Preliminary results indicate significant differences in the morphology of the crystals grown by directional solidification when a free surface is present in a vertical downward growth (gravity in the direction opposite to the growth direction).

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Biotechnology

Dr. D.E. Brooks of the University of Oregon is conducting a research program in cell partitioning in two polymer aqueous phases. Cell-partitioning techniques are being developed as an analytical and preparative procedure for biomedical research and biotechnology. In 1984, polymer phase systems were flown on the KC-135 aircraft for comparison with space shuttle experiments. Ground-based research is also being conducted in electrophoresis technology to obtain an improved understanding of the hydrodynamic and electrokinetic processes involved.

Metals and Alloys

Dr. Ared Cezairliyan of the National Bureau of Standards initiated an investigation using the KC-135 aircraft to determine if pulse calorimetry techniques for measuring the thermophysical properties of metals can benefit from low gravity. Earth-based techniques restrict the measurements to solids because the liquid zone falls when a metal becomes molten. Initial tests have shown that a liquid zone (using niobium) can be maintained at up to 50° of superheat.

Dr. Mary Helen McCay of the Marshall Space Flight Center conducted an investigation to solidify samples of MAR-M246 in low gravity and compare these to ground-processed specimens. MAR-M246 is a nickel-based superalloy with carbon and boron fibers that is used in high-temperature applications. The samples produced in low gravity had a different secondary dendrite spacing, a decrease in carbide volume fraction, and a carbide shape change. These results could enhance the high-temperature properties.

A series of F-104 flights have been conducted to quench samples of cast iron in low gravity. The tests were conducted to determine if grey iron could be cast in the low-gravity time available in the aircraft. This work has been conducted in cooperation with John Deere and Company.

Glasses and Ceramics

The ability to prepare inorganic oxide glasses can be limited by the tendency of the melt to heterogeneously nucleate and crystallize from the container wall. Under low-gravity conditions, which enable containerless processing, it should be possible to prepare glasses containing different and greater modifying ion content than could be

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accomplished on Earth. Researchers at the Jet Propulsion Laboratory have been involved in research in this area with the objective of eventually conducting flight experiments.

Combustion

Flammability-limits research is being performed by Professor Roger Strehlow of the University of Illinois. Six experiments have been performed in a series of Learjet flights, providing the first low-gravity flame tube experiments in which flames could proceed to completion. The unique three-axis acceleration measurements recorded in synchronization with the flame experiments have provided data that are now being used to examine correlations between gravity perturbations and the stability and speed of flame propagation.

Fluid Dynamics and Transport Phenomena

Two areas of research concentration on fluid dynamics and transport phenomena are oscillatory motions of liquid drops and geophysical fluid flow experiments and complementary theoretical studies. The latter topic, being pursued by John Hart, is discussed in Chapter 8B. Additional work on semiconductor crystal growth and metals and alloys has led to major advances in the understanding of phenomena such as surface-tension convection, thermosolutal flows, transient phenomena in fluid transport, electromagnetic effects on fluid flows, and Marangoni flows.

In addition, the PACE program contains a ground-based element to provide for research and technology development aiming toward flight experiments. The PACE program includes both basic research and the conceptual design of flight apparatus.

The ground-based program also includes four Centers of Excellence for the conduct of research in the above discipline areas. These centers include 1) the Materials Processing Center at the Massachusetts Institute of Technology, 2) the Institute for Theoretical Physics at the University of California at Santa Barbara, 3) the Bioprocessing and Pharmaceutical Research Center at University City Science Center, Philadelphia, and 4) the Center for Separation Science at the University of Arizona at Tucson. Each center receives a core grant, which may be allocated entirely at the discretion of the center. The centers will have participating researchers from both the industrial and academic communities, and they are expected

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Table 3 NASA Office of Space Science and Applications Microgravity Science and Applications Division

Experiment	Location	Principal Investigator	Sponsoring Center
PACE experiments: fluid physics			
Electrohydrodynamics	Princeton	D. Saville	LeRC[a]
Surface-tension-driven convection under reduced-gravity conditions	Case Western Reserve Univ.	S. Ostrach Y. Kamotani	LeRC
Free Surface Phenomena under low- and zero-gravity conditions	Case Western Berkeley Calif. Tech	P. Concus R. Finn D. Coles	LeRC
Surface-tension-induced instabilities in reduced gravity: the Benard problem	Univ. of Texas LeRC	E. Koschmieder A. Chal	LeRC
Mass-transport phenomena between bubbles and dissolved gases in liquids under reduced-gravity conditions	Univ. of Toledo	K. Dewitt	LeRC
Test of new thermodynamic model of impurity extraction by droplets	National Bureau of Standards	G. Morrison J. Kinkaid	LeRC
PACE experiments: critical phenomena			
Specific heat of helium through the lambda point	Stanford Univ.	W. Fairbank J. Lipa	JPL[b]
Light-scattering tests of fundamental theories of transport properties in the critical region	National Bureau of Standards	M. Moldover	LeRC
Precise viscosity measurements very close to critical points	National Bureau of Standards	M. Moldover	LeRC
Critical transport phenomena in fluid helium under low gravity	Duke Univ.	H. Meyer R. Behringer	GSFC[c]

[a]LeRC is the Lewis Research Center.
[b]JPL is the Jet Propulsion Laboratory.
[c]GSFC is Goddard Space Flight Center.

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to obtain significant additional funding from industrial sources as well as state and local governments.

Another element of the ground-based research program is the Microgravity Materials Science Laboratory (MMSL), located at the NASA Lewis Research Center. The purpose of the MMSL is to provide access to industry, academic, and government researchers who wish to conduct materials science and technology research on experimental apparatus similar to that being flown on the space shuttle. The MMSL will be fully equipped with materials research and analysis facilities and will be supported by the materials characterization and computational capabilities of the Lewis Research Center. The MMSL facility will be used to explore the baseline 1-g behavior of materials or processing phenomena in support of reduced gravity experimentation on the space shuttle and later on the space station.

Current research projects being conducted under the auspices of the Microgravity Science and Applications Division of NASA are listed in "Microgravity Science and Applications Program Tasks," NASA TM-87568, 1985 (see Table 3).

Mechanisms for Academic and Industrial Participation

Civilian research in space is coordinated through NASA, which provides transportation to and from space, qualifies and integrates experimental payloads with other payloads sharing the space shuttle or other space vehicle, and coordinates or controls the conduct of experiments performed in space. Some research is funded entirely by NASA; other research may be funded by private sources in coordination with NASA. NASA maintains three provisions for partial sponsorship of research in space, Joint Endeavor Agreements, Technical Exchange Agreements, and Industrial Guest Investigator programs. University and industrial researchers may submit proposals directly to NASA for funding or to other government agencies such as the National Science Foundation (NSF).

Commercial Activities

NASA maintains a commitment to the commercial use of space and has formulated outreach programs to industry. Joint Endeavor Agreements, Technical Exchange Agreements, and the Industrial Guest Investigator programs are mechanisms for involving commercial enterprises in the conduct of research in a low-gravity environment.

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Summary

Scientific research in a low-gravity environment has now been conducted for over 20 years in support of the U.S. space program. Research efforts were initially designed to support NASA's mission, but with the emerging operational status of the space shuttle, the focus of low-gravity research is expanding into many fundamental areas of science and engineering. This research promises to make significant contributions to our knowledge base.

In support of low-gravity research, NASA has developed a very extensive array of experimental facilities for both ground-based and space-based research. These facilities are now available for researchers in academia, industry, and national laboratories for experimentation in areas that promise significant scientific or engineering contributions. In addition, a major program of research funding, including the proposal review process, has been established within NASA, and funding for low-gravity research may be obtained from other sources, such as NSF, and coordinated with NASA for use of NASA facilities.

Researchers desiring to perform low-gravity research should, however, be aware that space-based facilities represent a limited resource that needs to be used efficiently and effectively. This almost demands that proposed research proceed through a logical progression from the development of theoretical models of phenomena to be researched, to ground-based research aimed at advancing the state of knowledge as far as possible before space-based research is initiated, to space-based research designed to extend the frontier of knowledge beyond that reasonably possible on Earth.

Acknowledgments

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Very High Resolution Phase Transition Experiments at Low Temperatures in Low Gravity

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Introduction

A second-order, or cooperative, phase transition often occurs when a system attains a new form of long-range order under selected external conditions. For example, if the density of a fluid is set to a particular value, called the critical density, and its initially high temperature is slowly reduced, it will pass through a critical point where it splits into two phases. Unlike a first-order phase transition, such as the melting of ice, this phenomenon is accompanied by highly anomalous fluid properties. The initially clear fluid becomes temporarily turbid, almost completely blocking light transmission; the thermal conductivity and viscosity approach very high values; and the velocity of sound tends toward zero. All of this activity occurs over a small temperature range, at most a few degrees wide.

Although widely studied for many years, cooperative transitions were poorly understood theoretically until recently. In the early 1970s, a new theoretical model of these transitions was developed, based on the application of the renormalization group (RG) technique by Kenneth Wilson.[1] This approach has led to specific, although approximate, predictions, [2a] for many experimentally determined parameters, most notably the critical exponents that characterize the asymptotic divergence of the thermodynamic variables in the limit as the temperature increment from the transition approaches zero. More recent models[3,4] based on the same techniques have permitted more sophisticated predictions, and it may soon be possible to characterize the complete singularity with a single function having few disposable parameters. To guide efforts in this direction and to test the correctness of the basic

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assumptions of the theory, it is essential to accumulate experimental data that probes both the most firmly established predictions and the latest tentative proposals.

Almost all the experimental tests of theoretical predictions for cooperative phenomena to date have encountered severe difficulties. Apart from the problems of measurement, very close to the transition, the singular behavior of thermodynamic parameters becomes distorted due to various defects in the sample itself. For example, in solid systems small variations of composition in different parts of a sample lead to different local transition temperatures. This leads to a smearing of the ideal transition over a finite temperature range, limiting the resolution of the test. Low-resolution tests suffer from other difficulties due to the asymptotic nature of the theory and the need to carry higher order terms far from the transition. At low temperatures, liquid helium (He) undergoes a unique second-order phase transition to the superfluid state, known as the lambda transition. Here the problems described above are minimized, making this transition the primary testing ground for the RG theory. Unfortunately, as discussed in the next section, the results of high-resolution experiments show small but significant discrepancies with theory. Because the experiments on the lambda transition represent the most severe tests of the theory conceived to date, it is important to develop them as fully as possible. Doing so promises to significantly extend our insight into the remarkable properties of cooperative transitions.

To obtain significantly better tests of the RG theory, it is not enough simply to increase the accuracy of the measurements. The existence of the nonasymptotic corrections makes this approach alone unattractive. Rather, it is also necessary to somehow break through the rounding barrier described above and obtain improved data that extends much more deeply into the asymptotic region near the transition. In the case of solid systems, sample defects are the main source of rounding, and improved materials processing is needed to allow progress. However, it appears very unlikely that the resolution achievable by this route would ever compete with that already available with fluid systems. For these systems, hydrostatic compression is the main source of rounding, and this effect can be reduced dramatically by performing experiments in space. For reasons described below, the lambda transition again provides the maximum potential resolution in this environment.

This paper briefly outlines the present status of testing the theory of second-order transitions and describes the potential value of additional experiments per-

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formed in space. The theoretical background for experiments on cooperative transitions is discussed, and some proposed experiments for space are described, with an emphasis on the currently developing lambda-point heat-capacity experiment. Some of the technology advances associated with this program also are described.

Background

Near a cooperative phase transition, many properties of a system exhibit singular behavior. In the limit, as the transition is approached, this behavior can be represented by simple mathematical forms. For example, in the case of a ferromagnet, the magnetization, M, below the transition can be written as

$$M \propto t^{\beta} \tag{1}$$

where $t = |T/T_c - 1|$ (T_c is the transition temperature) and β is a constant. The heat capacity, C, can be written as

$$C \propto t^{-\alpha} \tag{2}$$

where the exponent α is another constant. The primary task of cooperative transition theory has been to obtain values for the exponents (i.e., α, β) that can be compared with experimental results.

The RG theory has successfully explained the anomalies observed in systems over a wide range of states near their transition points and generally is credited with giving correct predictions, at least for the exponents. Why, then, does this theory need to be tested further? The answer is twofold. First, the vast majority of tests to date are weak at best. Second, it now is possible to enter a region never before studied, deep in the asymptotic region, where the theory makes relatively simple, clear-cut predictions. Amplifying the first point, the area in which many prior tests can be considered weak is that of data analysis. Wegner[5] has shown that in addition to the leading singular term there exist higher order singularities in the representation of thermodynamic parameters near cooperative phase transitions. The extended representation of a variable X(t) can be written as

$$X(t) = A_X t^{\Delta_X}(1 + a_X t^{\delta_X} + \ldots) + \ldots \tag{3}$$

where the exponents Δ_X and δ_X characterize the leading singularity and the confluent, or nonasymptotic, term, respectively. Typically a set of data obtained over two or three decades of the dimensionless parameter t is fitted to

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a theoretical expression of the type in Eq. (3) with four or five disposable parameters. Because the full expression may have more than eight such unknowns, allowing for different values on each side of the transition, a compromise must be reached. Usually the less important parameters are set to zero or constrained with theoretical guidance. This hybridized model is then fitted to the data. At the extremes of the fitting region where departures are seen, data are rejected on the grounds that the model is not adequate there. The resulting good fit with four or so free parameters is then taken as support for the theory! With so many free parameters and wide discretion in the rejection of data, it is hardly surprising that seemingly reasonable model fits can be obtained. This lamentable situation has been noted by others, as illustrated by the following quotation from a paper by H. Guttinger and D. Cannell[6]:

> The experience we have had in "forcing" data to fit the current theoretical framework involving correction terms has made it clear to us that almost any reasonable data set can be brought into very good agreement with theory, primarily because of the tremendous flexibility afforded by the correction terms. When one couples this flexibility with the additional flexibility and complexity generated by revisions to scaling, it is clear that theory is in an almost unassailable position. Consequently, any theoretical progress which would reduce the number of effectively free parameters would be extremely valuable.

In general, the RG predictions are more easily established for the static, or equilibrium, properties than for the dynamic, or transport, properties. The present status of the comparison between theory and experiment in these two areas is sketched in the next sections.

Static RG Predictions

Recent estimates for the exponents associated with a number of thermodynamic parameters are given in Table 1. The amplitudes, A_x and a_x, which are system-dependent, are far more difficult to estimate, although certain universal ratios have been predicted. Very recently, Bagnuls and Bervillier[3] and Dohm[4] have presented more sophisticated tests, which go beyond the ideas incorporated into Eq. (3). These tests aim to reduce the number of free parameters by making maximum use of the universal

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features of the RG Hamiltonian, which leads to additional calculable constraints. To date, this approach has not yielded any significant new results, but it has the potential of leading to a very unambiguous test of the theory.

The most advanced tests of the RG predictions for cooperative phase transitions are derived from experiments performed near the lambda transition of He. As is well-known, this transition has several experimental advantages not found in other systems. For example, because the system is superfluid below the transition, thermal relaxation times are short, and even above the transition temperature, the thermal conductivity diverges. Also, because it is a fluid system, the problems with strains and crystal defects encountered with solids are avoided. However, probably the most important reason is that, in contrast to the behavior of a fluid near its critical point, the divergence of the compressibility is very weak, thus minimizing gravity rounding from this effect.

At the lambda point, tests of the static theory center on the determination of two exponents, α and ζ, which characterize the leading singularities of the heat capacity and the superfluid density, respectively

$$C_p = At^{-\alpha}(1 + Dt^x + \ldots) + B \tag{4}$$

and

$$\rho_s/\rho = A_\rho t^\zeta (1 + D_\rho t^{x_\rho} + \ldots) \tag{5}$$

where ρ and ρ_s are the total and superfluid densities, respectively. In addition, information is obtained on the leading coefficients and other parameters in these expressions.

Table 1 Theoretical estimates of critical exponents based on RG calculations

	n[a]=0	n=1	n=2	n=3
γ	1.1615±0.0020	1.241±0.0020	1.316±0.0025	1.386±0.0040
υ	0.588±0.0015	0.630±0.0015	0.669±0.0020	0.705±0.0030
η	0.027±0.004	0.031±0.004	0.033±0.004	0.033±0.004
β	0.302±0.0015	0.325±0.0015	0.3455±0.0020	0.3645±0.0025
$\eta(2)$	-0.2745±0.0035	-0.3825±0.0030	-0.474±0.0025	-0.549±0.0035
α	0.236±0.0045	0.110±0.0045	-0.007±0.006	-0.115±0.009
$\Delta,\omega\upsilon$	0.470±0.025	0.498±0.020	0.522±0.018	0.550±0.016

[a]n is the number of degrees of freedom of the order parameter.

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When applied to the lambda point, the RG model gives predictions[2] for the exponents α, α', ζ, x, and x_ρ, the coefficient ratios A/A', D/D', and D'/D_ρ, and the difference $B - B'$, where the primed quantities refer to Eq. (4) below the transition. Also, the universality hypothesis[7] predicts that the above quantities will be independent of "irrelevant" variables, in this case the pressure and ^{3}He concentration, and scaling[8] predicts that $\alpha = \alpha'$. Table 2 lists the theoretical predictions for the above quantities, along with the experimental results. The detailed comparison of theory and experiment is described elsewhere.[9] Very briefly, it was found that 1) the apparent agreement for ζ in Table 2 may be fortuitous, because previous experimental analyses did not allow fully for the nonlogarithmic divergence of the heat capacity, which is used to derive the superfluid density data from other measurements; and 2) significant discrepancies still exist in the various determinations of α. The most precise measurements of this exponent are summarized in Table 3.

It is unfortunate that even the best high-resolution tests of the RG theory show small but persistent departures from the predictions. It would appear to be of very high priority to attempt a resolution of these discrepancies. Clearly, only the lambda transition has significant potential for improving the experimental results, because of the unique properties of this system. By performing new measurements at higher resolution, perhaps approaching $t \approx 10^{-12}$ on the space station, the dynamic range of the measurements can be extended significantly. Improved

Table 2 Comparison of observed and predicted values of parameters in Eqs. (4) and (5) for the lambda transition

Parameter	$\alpha(=\alpha')$	A/A'	x	D/D'	$B-B'$	ζ	D'/D_ρ
RG predictions	$-.008 \pm .003$	1.03	$0.521 \pm .006$	1.17	0	$.669 \pm .002$	$.15 \pm .18$
ρ_s data	-	-	$.5 \pm .1$	-	-	$.6749 \pm .0007$	$-.17$
Isobaric expansion data	$-.026 \pm .004$	$1.112 \pm .022$	$(=.5)^a$	$1.29 \pm .25$	(=0)	-	$\pm .04$
^{3}He-^{4}He mixtures	-.022	1.088	(=.5)	-	(=0)	-	-

[a]Quantities in parentheses represent constraints.

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thermometry also will allow more accurate measurements over the whole range, further increasing our knowledge of the asymptotic form of the singularity.

Dynamic RG Predictions

Although in principle the representation of transport properties is similar to that given in Eq. (3) for equilibrium properties, convergence of the series is commonly much slower. In cases of importance (e.g., the thermal conductivity of He near the lambda point), more complex numerical models are used that involve nonlinear RG schemes. Testing of the models involves the evaluation of more parameters, because there are less known constraints; thus, this area is not so well developed. As in the case of static properties, the lambda point is at the forefront of the confrontation between experiment and theory. Of primary importance is the behavior of the thermal conductivity above the transition temperature. In this case, the value of δ_X in Eq. (3) appears to be .05 or less, causing significant difficulty in determining Δ_X. Theory testing is therefore based on model fitting at rather large values of t, not in the true asymptotic region. The results of this approach are still less than satisfactory.

Table 3 Summary of experimental determinations of the heat-capacity exponent at the lambda transition (n=2)

Group	Ref.	Parameter	α	Range of t
Ahlers	14	C_{Sat}	$0.000 \leq \alpha \leq 0.025$	$10^{-6} \rightarrow 3 \times 10^{-3}$
Ahlers	15	C_{Sat}	$-.0163 \pm .0017$	$10^{-6} \rightarrow 3 \times 10^{-3}$
MAP	15	Expansion Coefficient	$-0.026 \pm .004$	$3 \times 10^{-5} \rightarrow 3 \times 10^{-3}$
G & M	16	C_{Sat}	$-.0198 \pm .0037$	$10^{-6} \rightarrow 3 \times 10^{-3}$
G & M	16	Mixtures	$-.025$	$3 \times 10^{-6} \rightarrow 3 \times 10^{-3}$
T & W	17	C_{Sat}	$-.017$	$10^{-5} \rightarrow 2 \times 10^{-3}$
T & W	17	Mixtures	$-.024$	$10^{-5} \rightarrow 3 \times 10^{-3}$
L & C	18	C_{Sat}	$-.013 \pm .002$	$10^{-8} \rightarrow 10^{-3}$

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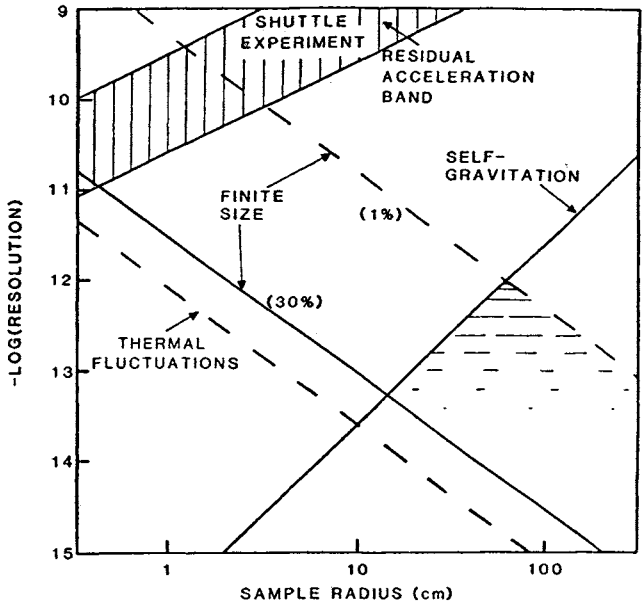

Fig. 1 Comparison of the factors limiting the ultimate resolution of the lambda transition in space.

Low-Gravity Experiments Near the Lambda Point

Transition Broadening in Space

In a spacecraft environment, which has no external forces and is far from all sources of gravitational fields, the lambda transition would be broadened by at least three effects. First, the divergence at the transition temperature of the length, r_c, over which density fluctuations are correlated, leads to finite-size rounding. This effect is minimized by the use of large samples with high volume-to-surface area ratios. It is easy to show that for a spherical sample, a nominal 1% correction to a bulk property of the fluid occurs when

$$t = 4.6 \times 10^{-10} r_s^{-3/2} \quad (6)$$

where r_s is the radius of the sample in centimeters. The transition will be completely smeared out when $r_s \approx r_c$, giving a second relation

$$t = 2.8 \times 10^{-12} r_s^{-3/2} \quad (7)$$

Second, Goldstein[10] has noted that temperature fluctuations

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ultimately will wash out the transition. This effect occurs at

$$t = 8.7 \times 10^{-13} r_s^{-3/2} \tag{8}$$

which is somewhat less than the previous limits. The third effect is due to the self-gravitation of the He, generally an exceedingly small effect, which nevertheless sets an ultimate limit on the sharpness of the transition. For a self-gravitating sphere of He in hydrostatic equilibrium, it is easy to show that the pressure difference, ΔP, between the surface and the center is given by

$$\Delta P = 2\pi/3 \rho^2 G r_s^2 \tag{9}$$

where G is the gravitational constant. Since the transition broadening is just

$$\Delta t = \Delta P/T_\lambda (dP/dT)_\lambda^{-1} \tag{10}$$

where $(dP/dT)_\lambda$ is the slope of the lambda line, the following result is obtained

$$\Delta t = 2.6 \times 10^{-16} r_s^2 \tag{11}$$

The above expressions are plotted in Fig. 1, which shows that the maximum possible resolution is $t \approx 10^{-12}$, with the application of minor corrections to the data and $t \approx 10^{-13}$, if extensive correction terms are used. These levels represent the best that can be achieved in any presently envisaged system and extend four to five orders of magnitude beyond that which can be achieved on Earth.

In more practical situations, effects other than self-gravitation usually set the upper limit on the sample size. For example, for a free-flying spacecraft in low Earth orbit that is maintained drag-free to a level of 10^{-8} g or better, one also must consider tidal forces due to the Earth's field and gravitational fields due to the mass distribution of the vehicle. On board the space shuttle, residual acceleration in the range 10^{-3} g to 10^{-4} g competes with the finite-size effect to limit the resolution. Optimization of the sample size to minimize the total distortion can be performed by combining Eqs. (6) and (10) and replacing ΔP with $2\rho a r_s$, where a is the acceleration. This procedure leads to a sample size that minimizes the combined distortion and maximizes the attainable resolution. The results of the optimization calculations are summarized as a function of g in Table 4. In a shuttle environment of 10^{-4} g, a resolution of 2×10^{-10} could be obtained, which is about two orders

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Table 4 Optimum sample size, r_s, and corresponding temperature resolution, Δt, as a function of residual acceleration, a

a(g)	Δt	r_s (cm)
1	5.0×10^{-8}	0.088
10^{-1}	1.3×10^{-8}	0.22
10^{-2}	3.2×10^{-9}	0.56
10^{-3}	7.9×10^{-10}	1.40
10^{-4}	2.0×10^{-10}	3.5
10^{-5}	5.0×10^{-11}	8.8
10^{-6}	1.3×10^{-11}	22.2
10^{-9}	2.0×10^{-13}	351.0

of magnitude higher than is possible on Earth. For comparison, at the critical point of a typical fluid, the maximum resolution on the shuttle is expected to be[11] of the order 10^{-8}, which is similar to the lambda-point resolution on the ground.

Testing the RG Theory

In the previous section, the potential resolution available at the lambda point in various low-gravity experiments was estimated. On the shuttle, a resolution in the 10^{-10} range can be achieved, depending on the level of acceleration noise. At this resolution a major advance can be made in the study of both static and dynamic critical phenomena. Figure 2 shows the historical development of the resolution of cooperative transitions. The data are not intended to be inclusive but are representative of the progress in a given era. The points connected by the solid line represent the resolution at which data were available to allow some type of theoretical test; the stars represent in a loose sense the "ultimate" resolution quoted. Clearly, there is a large unexplored region, at least on a logarithmic scale, beyond the gravity cutoff on Earth, where experiments could add substantially to our knowledge of cooperative transitions.

It is easy to imagine many experiments that could be performed in this region, extending the range of the ground-based measurements. An example of such an experiment is the lambda-point heat-capacity project being readied for shuttle flight in 1988. The instrument being developed to perform the experiment is shown in Fig. 3. Figure 4 shows a schematic view of the overall system. The heat-capacity apparatus will be housed in a flight-qualified He Dewar, such as the Jet Propulsion Laboratory

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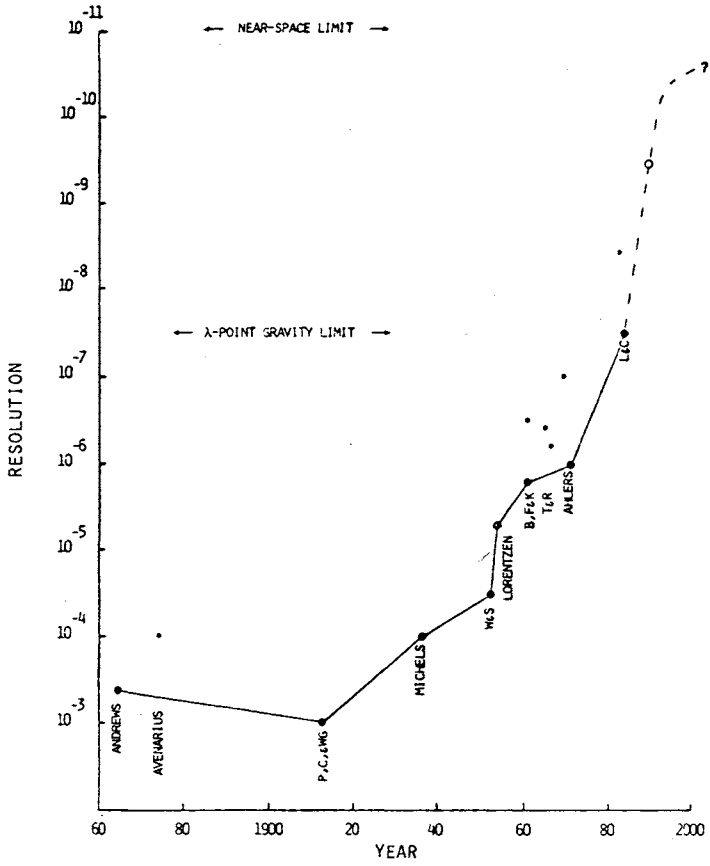

Fig. 2 Historical development of resolution of cooperative transitions.

superfluid He facility. A Dewar control system manages the He venting and Dewar temperature and records the information from a local three-axis accelerometer. The experiment is controlled by two systems: a thermal control system, which takes care of the thermal-isolation-system set points as a function of experiment mode; and a main experiment control system, which sets the mode, logs the data, and communicates with the shuttle's aft flight deck. Once in operation, the project would comprise three primary modes. The first mode involves coarse setup of the thermal control system and calibration. Next, there will be a wide-range heat-capacity data-collection mode used to bridge the gap between ground-based data and the highest resolution measurements. The third mode will be used for

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high-resolution measurements, to be activated during periods of low acceleration.

In addition to measuring heat capacity, other experiments clearly are possible near the lambda point, some of which are listed in Table 5. Also listed are a number of other experiments on He that can exploit the technology advances needed for the lambda-point work. In the He system, there are two pure-fluid critical points--two lambda lines as a function of pressure and ^{3}He concentration and a tricritical point in ^{3}He-^{4}He mixtures. All these systems will have somewhat different exponent values and can benefit from being studied in space. Both static and dynamic properties can be studied by using different experiment modules, allowing a wide range of potential tests for the RG theory.

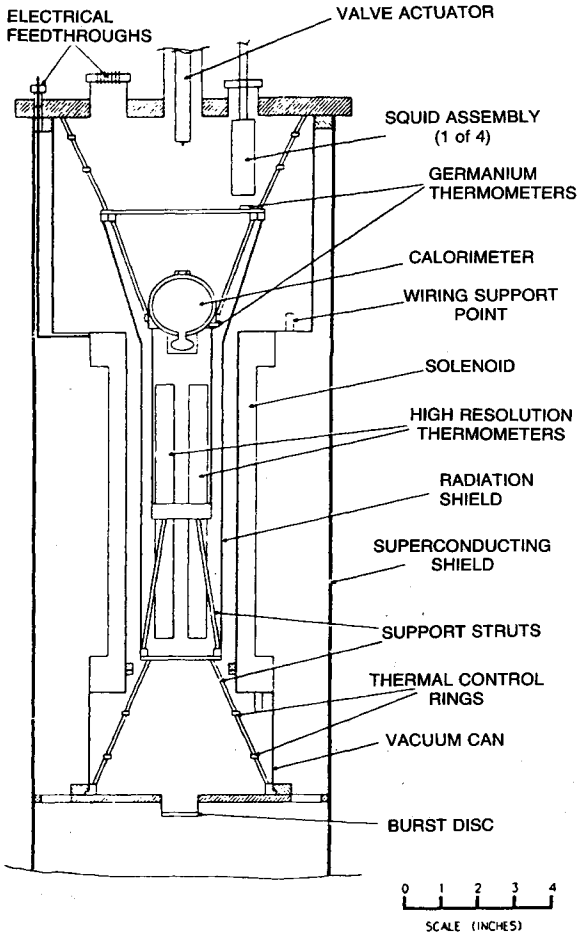

Fig. 3 Thermal control system for flight experiment.

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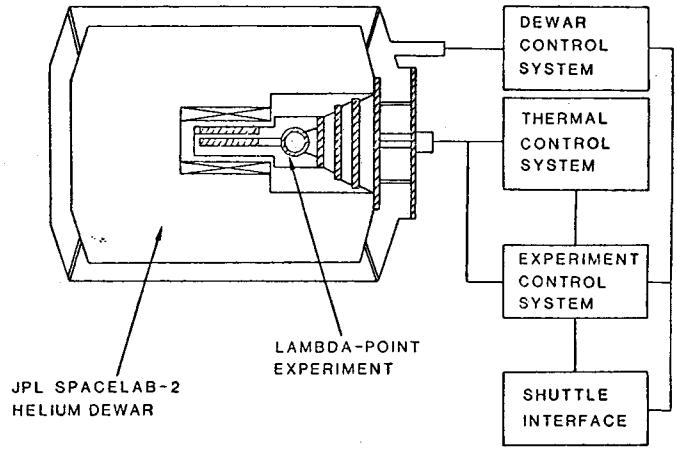

Fig. 4 Schematic view of main components of lambda-point flight experiment.

Table 5 Possible cryogenic experiments in the area of cooperative phenomena that could be improved in low-gravity conditions

Static scaling at the lambda point

- Measurement of the superfluid density
- Heat capacity of ^{3}He-^{4}He mixtures
- Heat capacity as a function of pressure

Dynamic scaling at the lambda point

- Thermal conductivity of ^{4}He above transition
- Thermal conductivity of ^{3}He-^{4}He mixtures
- Second sound damping coefficient below transition

Observation of new phenomena at the lambda point

- Crossover to 2-dimensional behavior
- Finite size effects in controlled geometries
- Proximity effect near the He-I/He-II interface
- Josephson effects in He

Critical point measurements

- Heat capacity of ^{3}He and ^{4}He
- Thermal conductivity and viscosity of ^{3}He and ^{4}He above T_c
- Order parameter measurements below T_c

Tricritical point measurements

- Heat capacity singularity
- Concentration susceptibility

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Technology Developments

The experiments described require several technology developments that are significantly more complex than those usually encountered in the laboratory. To exploit the potential resolution available in space at the lambda point requires significant advances in thermometry and thermal control. A low-gravity superfluid He facility also is needed, and the experiment design must be adapted for space. This section describes some of the development work performed for the lambda-point program.

Thermometer Development

At the start of the program, the highest resolution thermometers suitable for studying the lambda transition were carbon and germanium resistors. With these devices, it is possible to resolve to $t \approx 10^{-7}$ at the lambda point when the measuring power is about 10^{-8} W. Higher resolution can be obtained with increased dissipation, but with present readout technology, a power level of about 10^{-2} W would be needed to resolve down to $t \approx 10^{-10}$. Clearly, this is a high level for any low-temperature experiment, but especially for heat-capacity measurements in which one must measure power levels of the order of 10^{-10} W. This simple estimate underlines the importance of developing a completely different concept in high-resolution thermometry to study the lambda transition with subnanokelvin resolution.

A new thermometer was developed using a superconducting readout system and a paramagnetic salt as the sensitive element. This device has an exceptionally low intrinsic dissipation level ($<10^{-17}$ W) and a very high sensitivity because of the use of a Superconducting Quantum Interference Device (SQUID) magnetometer as a detector. Similar devices have been built[12] for use below 1 K, but their noise characteristics were not reported. A thermometer was constructed that was optimized for use near the lambda point of He and equipped with considerably improved shielding to minimize the effect of external magnetic fields. The construction of this device is described in Ref. 13. A schematic view of the thermometer is shown in Fig. 5. A fundamental limit on the resolution of this device is set by thermal fluctuations. Mean squared noise due to thermal fluctuations in the system is given by

$$\langle \Delta T^2 \rangle = 2kT^2/c_e\tau\ \tau_o \qquad (12)$$

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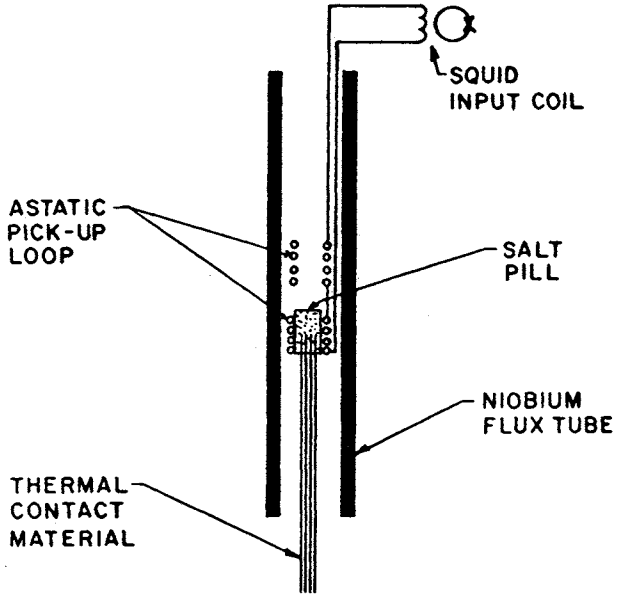

Fig. 5 Schematic view of paramagnetic salt thermometer.

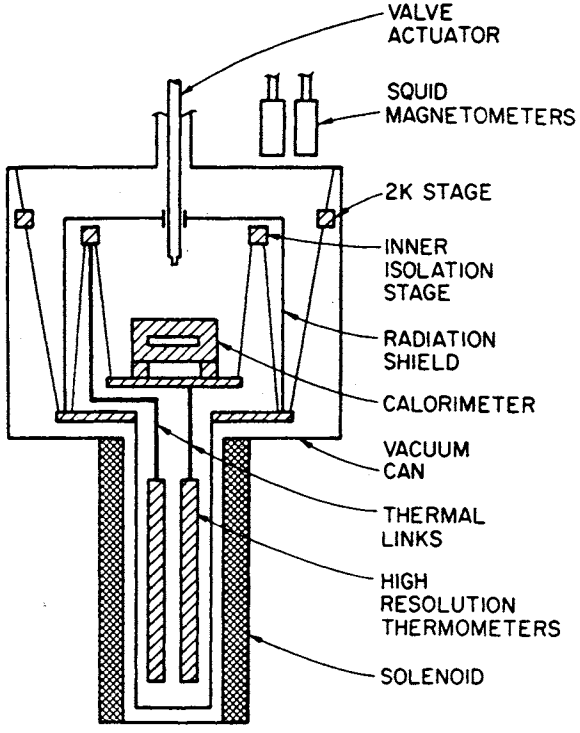

Fig. 6 Multistage thermal control system developed for laboratory use.

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where k is Boltzmann's constant, c_e is the heat capacity of the sensing element, τ is the integration time, and τ_o is the thermometer relaxation time for heat transfer to the He sample. At the lambda point, we obtain

$$\delta t_{rms} = \langle \Delta T^2 \rangle^{1/2} / T_\lambda \approx 4 \times 10^{-10} \qquad (13)$$

which is in reasonable agreement with the observed noise. The thermometer output signal has been integrated down to a 0.01 Hz bandwidth, providing a significant improvement in sensitivity beyond the level in Eq. (13). However, the thermal control system then in use did not provide the stability required for accurate measurements. Nevertheless, it appears to be relatively straightforward to obtain sensitivities in the 10^{-11} range under narrow-bandwidth conditions. Eq. (12) illustrates that thermal-fluctuation noise also can be reduced by minimizing the ratio τ_o/c_e, which contains the only physical design variables. It would appear possible to obtain a further reduction of an order of magnitude in this quantity before construction of the device becomes prohibitively difficult, which would reduce δt_{rms} by a factor of about three.

Thermal Control System

A second factor limiting the accuracy of high-resolution heat-capacity measurements is stray-heat leak control. An advanced thermal control system designed to minimize this problem is shown in Fig. 6. It contains four stages of thermal isolation and includes a thermal shield completely surrounding the calorimeter, which can be temperature-controlled to within a few nanodegrees kelvin as measured by a paramagnetic salt thermometer. This shield isolates the calorimeter from ambient and stray room-temperature radiation, and from gas-transfer effects associated with temperature changes elsewhere in the system. The outer stages of isolation are thermally controlled with conventional resistance thermometry. This system has been in operation in the laboratory for a number of years and has been shown to provide adequate control for an experiment on the shuttle. The flight version of this system is shown in Fig. 3.

Helium Facility

To reduce the cost and effort of cryogenic experiments in space, the Jet Propulsion Laboratory has constructed a reusable, flight-qualified superfluid He Dewar. This facility carried a first set of experiments on the

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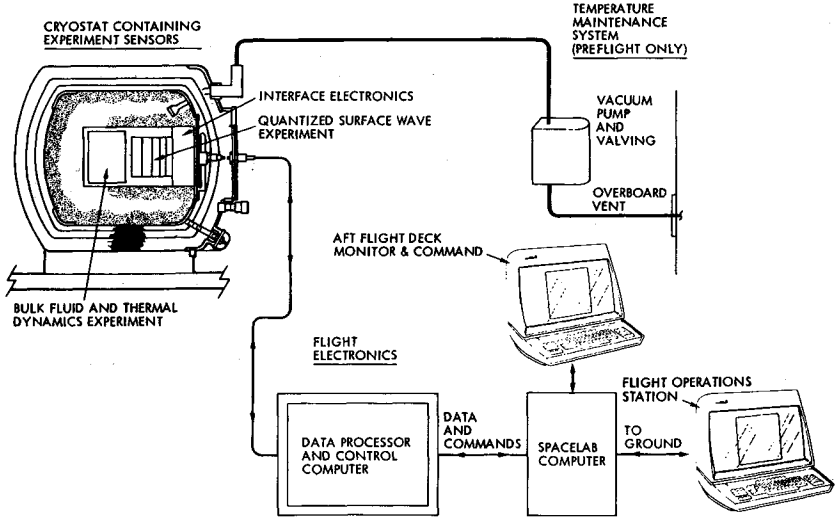

Fig. 7 Schematic view of Jet Propulsion Laboratory superfluid helium facility.

shuttle in 1985 as part of the Spacelab-2 program. In the first flight, the cryostat was located on a pallet in the shuttle cargo bay and had all the electronic interfaces necessary to control experiment parameters from the shuttle cabin and from the ground. A schematic view of the system is shown in Fig. 7. Experiments can be mounted on a cover plate that seals the He tank, and they can interface with external electronics via an evacuated feedthrough area. The Dewar is filled with liquid He several days before launch and maintained in the superfluid state with a small vacuum pump. Once on orbit, the system is vented to space through a set of orifices selected to maintain the desired operating temperature in the range from 1.5 to 2.2 K. After equilibrium is established, the Dewar temperature is stable to within a few millidegrees kelvin throughout the remainder of the flight.

Summary

This paper has discussed the motivation and potential for performing advanced, very high resolution tests of the theory of cooperative phase transitions in low-gravity conditions. Clearly, tests extending deep into the asymptotic region near the transition can be performed; it is in this region that the theoretical predictions assume their

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simplest form. This advantageous situation should lead to a major improvement in our understanding of the range of applicability of current theoretical ideas in this field. Of the various phase transitions, research on the lambda transition holds the greatest potential for advancing science. With the application of advanced cryogenic techniques, the potential of this system should be realized. The technology for the initial experiments already is well-developed, and the first results are expected in late 1988. Follow-on experiments of increasing sophistication no doubt will occur, and ultimately experiments may be conducted on a space station. The advantages of that environment would be extended observation time and the possibility of submicrogravity conditions. It is hoped that the possibilities described here also will stimulate additional theoretical effort in this exciting area of physics.

References

[1]Wilson, K.G., "Renormalization Group and Critical Phenomena," Phys. Rev., Vol. B4, 1971, pp. 3174-3183.

[2]LeGuillou, J.C. and Zinn-Justin, J., "Critical Exponents From Field Theory," Phys. Rev., Vol. B21, 1980, pp. 3976-3998.

[2a]Brezin, E., LeGuillou, J.C., and Zinn-Justin, J., "Universal Ratios of Critical Amplitudes Near Four Dimensions," Phys. Lett., Vol. 47A, 1974, pp. 285-287.

[3]Bagnuls, C. and Bervillier, C., "Towards an Unambiguous Test of Renormalization Group Predictions for Critical Behavior," preprint.

[4]Dohm, V., "General Relation between Specific Heat Above and Below a Second Order Phase Transition," Phys. Rev. Lett., Vol. 53, 1984, pp. 1379-1382.

[5]Wegner, F.J., "Corrections to Scaling Laws," Phys. Rev., Vol. B5, 1972, pp. 4529-4536.

[6]Guttinger, H. and Cannell, D., "Corrections to Scaling in the Susceptibility of Xenon," Phys. Rev., Vol. A24, 1981, pp. 3188-3204.

[7]Kadanoff, L.P., "Scaling, Universality, and Operator Algebras," Phase Transitions and Critical Phenomena, Vol. 5A, edited by C. Domb, M. S. Green, Academic Press, NY, 1976, pp. 1-34.

[8]Widom, B., "Surface Tension and Molecular Correlations Near the Critical Point," J. Chem. Phys., Vol. 43, 1967, pp. 3892-3897.

[9]Lipa, J.A., "High Resolution Heat Capacity Measurements Near the Lambda Point," Proceedings of Near Zero Conference, Stanford University, Stanford, CA, 1986, in press.

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[10]Goldstein, L., "Lambda Transformation of Liquid Helium Four," Phys. Rev., Vol. 135, 1964, pp. 1471-1480.

[11]Moldover, M.R., Sengers, J.V., Gammon, R.W., and Hocken, R.J., "Gravity Effects in Fluids Near the Gas-Liquid Critical Point," Rev. Mod. Phys., Vol. 51, 1979, pp. 79-99.

[12]Giffard, R.P., Webb, R.A., and Wheatley, J.C., "Principles and Methods of Magnetic Measurements Using an rf-Biased Superconducting Device," J. Low Temp. Phys., Vol. 6, 1972, pp. 533-610.

[13]Lipa, J.A., Leslie, B.C., and Wallstrom, T.C., "A Very High Resolution Thermometer for Use below 7°K," Physica (Utrecht), Vol. 107B, 1981, pp. 331-332.

[14]Ahlers, G., "Experiments Near the Superfluid Transition," Physics of Liquid and Solid Helium, edited by K.H. Bennemann, and J. B. Ketterson, John Wiley & Sons, NY, 1976, pp. 85-206.

[15]Mueller, K.J., Ahlers, G., and Pobell, F., "Thermal Expansion Coefficient Near the Superfluid Transition of ^{4}He Under Pressure," Phys. Rev., Vol. B14, 1976, p. 2096-2118.

[16]Gasparini, F.M. and Moldover, M.R., "Specific Heat of ^{4}He and ^{3}He-^{4}He Mixtures at Their Lambda Transition," Phys. Rev., Vol. B12, 1975, pp. 93-113.

[17]Takada, T. and Watanabe, T., "Specific Heat Near the Lambda Point in ^{4}He and ^{3}He-^{4}He Mixtures," J. Low Temp. Phys., Vol. 41, 1980, pp. 221-241.

[18]Lipa, J.A. and Chui, T.C.P., Phys. Rev. Lett., Vol. 51, p. 2291, 1983.

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Low-Gravity Experiments In Critical Phenomena

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Scope of Review

The research area denoted by "critical phenomena" roughly concerns those properties of a many-body system that depend on the system being sufficiently close to a critical point that the correlation length characterizing the size of fluctuations in the system greatly exceeds the range of the interparticle interactions that initially caused the appearance of the critical point. In this regime, the anomalous thermodynamic, transport, and structural properties of interest are independent of many of the details of the underlying interactions. Thus, the same anomalies occur in diverse physical systems. This is a universality that has excited research in many disciplines in the last 20 years. Kenneth Wilson's Nobel Prize in Physics was awarded (1982) largely for developing the theoretical framework used to explain and compute these universal anomalies.

This review begins with the definition of a few terms that are widely used in this research area. A very general description of the nature of current theoretical predictions concerning critical phenomena follows. These predictions are concerned with asymptotic properties near critical points. Thus, experimental tests are necessarily sophisticated. It is argued that fluid systems are attractive experimental systems for such tests because they (in contrast to most solids) can be brought into thermodynamic equilibrium on laboratory time scales. A discussion of the ways in which gravity affects experiments with fluid systems follows. The art of measuring many thermodynamic properties and certain transport properties near critical points in fluid systems has advanced to the point that the ability to test theory on Earth is limited by the density stratification produced by Earth's gravitational field. Thus, serious efforts now are being made to extend mea-

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surements by exploiting the low-gravity environments that have become available with the space shuttle. Finally, several experiments planned for a low-gravity environment are described.

Liquid-vapor systems are emphasized and are contrasted with liquid mixtures. Liquid mixtures offer the possibility of reducing certain gravitational effects at the price of increasing the difficulty of attaining thermodynamic equilibrium and of describing the thermodynamic surface (because of the introduction of at least one additional degree of freedom).

Nomenclature for Critical Points

At the outset, it is convenient to distinguish between thermodynamic "field" variables and thermodynamic "density" variables.[1] Field variables are those variables that are identical in coexisting phases when such phases are in thermal equilibrium. The field variables that are used to define the state of a liquid-vapor system are any two of the triad: temperature (T), pressure (P), and chemical potential per unit mass (μ). Thermodynamic density variables are those variables that are different in coexisting phases at equilibrium. Examples of density variables that can be used to distinguish between the coexisting phases of a liquid-vapor system are the number of particles per unit volume (ρ) and the entropy density.

Because anomalies near critical points are of concern here and because the universal aspects of these anomalies are to be emphasized, dimensionless field variables are introduced that are used to measure the "distance" from a critical point. For liquid-vapor systems, appropriate variables are[2-4]

$$\tau \equiv t + e \cdot [\mu - \mu_0(T)] \cdot \rho_c/P_c \qquad (1)$$

and

$$h \equiv [\mu - \mu_0(T)] \cdot \rho_c/P_c \qquad (2)$$

The subscript c attached to a quantity denotes the system-dependent value of that quantity at the critical point; $t \equiv (T-T_c)/T_c$ is the reduced temperature measured from the critical temperature; $\mu_0(T)$ denotes the value of the chemical potential along the vapor-pressure curve below T_c and its smooth extension above T_c; and e is a system-dependent constant.

Critical points occur in a very wide variety of physical systems exhibiting phase transitions. Examples of

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critical points include the Curie point of a ferromagnetic or a ferroelectric solid, the Neel point of an antiferromagnet, the order-disorder transition of certain alloys (e.g., β-brass), the consolute point of binary liquid mixtures (i.e., the point at which partially miscible liquids become completely soluble), and the lambda transition of liquid ^{4}He (i.e., onset of superfluidity). In each of these systems, there is a density variable that is called the "order parameter," which is chosen to measure the difference between the two coexisting phases. For a liquid-vapor system, the order parameter is the scalar quantity

$$\Delta\rho^* \equiv (\rho_{\text{liquid}} - \rho_{\text{vapor}})/(2\rho_c) \qquad (3)$$

For an isotropic ferromagnet, a suitable order parameter is the vector $\vec{m}/m_0$. ($\vec{m}$ is the magnetization, and m_0 is its magnitude at zero temperature). As a critical point is approached along the path of two-phase coexistence, the order parameter continuously goes to zero. It is the gradual disappearance of the order parameter that most dramatically distinguishes critical points from other kinds of phase transitions such as melting, sublimation, and crystallographic phase changes.

Predictions for Thermodynamic Properties of Bulk Systems

To date, the renormalization group (RG) approach to critical phenomena has led to many predictions, which have been tested. These predictions include the division of experimental systems into "universality classes," the phenomenon of "scaling" of thermodynamic functions asymptotically close to critical points, specific numerical predictions for the critical exponents and the scaling functions associated with each universality class, and specific numerical predictions for the exponents and scaling functions associated with corrections to asymptotic scaling. The terms "universality classes," "scaling," and "critical exponents" are now discussed in the context of experimental tests involving fluids.

The universality classes for thermodynamic properties and static correlation functions are defined by the dimensionality (d) of the space the system is in, by the dimensionality (n) of the order parameter (e.g., n = 1 for a scalar, n = 3 for a vector in three dimensions) and by whether the interactions in the system are long-ranged. (In three dimensions, forces between static dipoles such as those in a ferroelectric are long-ranged. If the dipoles are mobile as in a polar fluid, the averaged force is short-ranged in this context.)

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Pure fluids near liquid-vapor critical points are three-dimensional systems with a scalar order parameter and short-ranged interactions (d = 3 and n = 1). Other systems in this universality class include three-dimensional Ising models; binary alloys (such as β-brass), which undergo order-disorder phase transitions; uniaxial ferromagnets; and binary liquid mixtures near consolute points. Theory predicts and experiments confirm that sufficiently close to these critical points each of these systems has identical thermodynamic anomalies in the sense defined below. Members of other universality classes have different thermodynamic anomalies. One system of interest is ^{4}He near its superfluid transition. This fluid system belongs to the class with d = 3 and n = 2 because its order parameter is a complex quantity. Tricritical points, where three phases become identical by the simultaneous vanishing of two independent order parameters, do occur in three-component liquid mixtures. They comprise yet another universality class (for each value of d and n).

The predictions concerning scaling can be summarized in variables appropriate for a liquid-vapor system by stating that sufficiently close to the critical point the thermodynamic potential can be written in the form[4-5a]

$$P(T,\mu)/P_c = P_0(\tau,h) + |\tau|^{\beta(\delta+1)} \cdot g_0(z) + c_1 \cdot |\tau|^{\beta(\delta+1)+\Delta} \cdot g_1(z) + \ldots \quad (4)$$

where $z \equiv h/|\tau|^{\beta\delta}$. Here, g_0 and g_1 are universal analytic functions of their arguments, and β, δ, and Δ are universal critical exponents. P_0 is an analytic system-dependent function, and c_1 is a system-dependent constant. The terms in Eq. (4) that have noninteger exponents are universal, and they are responsible for all the thermodynamic anomalies. The "scaling" property is that these terms, which might have been functions of the two variables h and τ, are, in fact, functions of a single variable z, which is a combination of these two. In principle, measurements of the pressure as a function of μ and T can be scaled by the factor $|\tau|^{\beta(\delta+1)}$ and replotted as a function of z (after subtraction of P_0). Close enough to T_c the data would collapse onto a single curve. In practice such data collapsing has been demonstrated with equation-of-state data[4] and specific-heat data[6] by using functions obtained by differentiation of Eq. (4). One of the strongest tests of Eq. (4) near a critical point has been made using an optical interferometer to study the density-versus-height profile of three fluids stratified under their own weight in Earth's gravitational field.[7] A successful demonstration of

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Table 1 Some accurate measurements of power laws for liquid-vapor systems

Property	Path	Power Law	Reference
Heat capacity ρC_v	$\rho=\rho_c$, $t<0$	$A^-(-t)^{-\alpha}$	8,9
Heat capacity ρC_v	$\rho=\rho_c$, $t>0$	$A^+(t)^{-\alpha}$	8,9
$(\rho_{liquid}-\rho_{vapor})/(2\rho_c)$	$h=0$, $t<0$	$B_0(-t)^{\beta}$	10,11
Symmetrized compressibility $(\partial\rho/\partial\mu)_T$	$\rho=\rho_c$, $t>0$	$\Gamma^+(t)^{-\gamma}$	11,12
Correlation length ξ	$\rho=\rho_c$, $t>0$	$\xi_0^+(t)^{-\nu}$	13

the scaling property requires determination of the exponents β and δ, the scaling function g_0, the critical parameters that appear in definitions of the variables τ and h, and often additional functions such as P_0. It is obvious that this requires a vast amount of data.

Once the functions (e.g., g_0, g_1) are known, Eq. (4) summarizes an infinite number of "power laws," all of which are related to the two noninteger exponents β and δ. For example, the density may be obtained from Eq. (4) through the relation $\rho = (\partial P/\partial\mu)_T$. One then can consider, for example, the behavior of ρ as the critical point is approached on special curves such as the coexistence curve, $h = 0$ (where $\rho \sim |\tau|^{\beta}$); the critical isotherm, $t = 0$ (where $\rho \sim |h|^{\delta}$); and the curve ($\tau = 0$). With few exceptions, the most exacting tests of the theory have been the measurements of a few properties on special curves. Some examples are listed in Table 1.

Except for ν, the exponents in these power laws are related to one another because they all result from differentiating the universal function g_0 (in Eq. [4]) with respect to τ and/or h and then evaluating the results at particular values of z. Typical relations among the exponents are $\alpha = 2 - \beta(\delta+1) \approx 0.11$ and $\gamma = \beta(\delta-1) \approx 1.24$, where the numbers quoted are appropriate for the $d = 3$, $n = 1$ class. In contrast to tests of scaling, the experimental study of power laws requires data along a single path through the critical point; thus, the measurement of critical exponents has received much more attention than tests of scaling.

With the exception of ξ_0^+, the coefficients of the tabulated power laws (i.e., the amplitudes) are related to one another because they also result from differentiating the universal function g_0 (in Eq. [4]) with respect to τ and/or h and then evaluating the results at particular values of z. A typical relation among the amplitudes[14,15]

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is $(A^+\Gamma^+/B_0) \approx 0.0599$, where the number quoted is appropriate for the d = 3, n = 1 class. The measurement of an amplitude ratio involves several power laws and provides information about the scaling function g_0.

The hypothesis that the singular terms in the thermodynamic potential ultimately arise from the divergence of the correlation length leads to the additional assertion[16] that the singular contribution to the free energy in a volume ξ^d is a finite universal quantity. This assertion has been called the hypothesis of "two-scale-factor universality." Two corollaries of two-scale-factor universality are the hyperscaling relation between exponents ($d\nu = 2 - \alpha$) and a group of amplitude relations between ξ_0^+ and the thermodynamic amplitudes. Typical relations between the amplitudes are

$$\xi_0 \cdot (A^+/k_B)^{1/3} \approx 0.26 \tag{5}$$

and

$$\xi_0 \cdot (B_0/\Gamma^+ k_B)^{1/3} \approx 0.67 \tag{6}$$

These corollaries mean that purely thermodynamic measurements can be used to determine the correlation length, a structural property, which usually is obtained from scattering experiments. Thermodynamic and scattering[12,17,18] measurements are consistent with the two-scale-factor universality hypothesis.

There are two aspects of all of the above predictions that have greatly complicated detailed experimental tests. The first is that the predictions are made in terms of abstract fields whose relationship to the thermodynamic field variables accessible to experiment is not known in advance. One expects that the abstract fields, sufficiently close to the critical point, can be approximated by linear combinations of the experimental field variables (as illustrated by τ and h in Eqs. [1] and [2]). In general, it is not possible to state what "sufficiently close" means. For some liquid-vapor systems, this issue has been carefully studied.[4,19] In these systems, the linear combination of variables in Eqs. (1) and (2) is consistent with data in an experimentally relevant range ($10^{-4} < |\tau| < 10^{-1}$ and $0.03 < |\Delta\rho^*| < 0.4$) if the system-dependent parameter e in Eq. (1) is chosen in the range $-0.02 < e < -0.005$.

The second complication in testing predictions is that the exponent Δ, characterizing corrections to scaling for many systems of interest, is near[20] 0.5, a number much less than 1. It follows that "sufficiently close," in the sense that correction terms are small, is close indeed. For

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example, the constant-volume heat capacity has the expansion as the critical temperature is approached from below

$$C_V = A^-(-t)^{-\alpha} \cdot (1 + A_1(-t)^{\Delta} + \ldots) \quad (7)$$
$$= A^-(-t)^{-0.11}(1 + A_1(-t)^{0.5} + \ldots)$$

If A_1^- is on the order of unity, $-t$ must be less than 10^{-4} if the second term is to be less than 1% of the first term. This condition is required if, for example, the exponent α is to be determined to roughly 1%.

It is useful to estimate the precision with which an experiment can determine the value of a critical exponent such as α. The simplest assumptions for this purpose are 1) the temperature can be measured with arbitrary accuracy, 2) C_V can be measured with a precision δC_V, 3) there are N decades of t available where t is sufficiently small that corrections to scaling of the form t^{Δ} are negligible and the precision of C_V is not degraded, and 4) the noncritical contribution to C_V is comparable to or smaller than the critical contribution. With these assumptions, the result is

$$\delta\alpha/\alpha = (\delta C_V/C_V)/(\alpha \cdot N \cdot 2.3) \approx (\delta C_V/C_V)/(0.25 \cdot N) \quad (8)$$

To determine α to 1% requires, for example, $\delta C_V/C_V \approx 0.005$ and $N \approx 2$.

The subjects mentioned up to this point are quite well developed theoretically and experimentally. For the dominant critical exponents (γ and δ) and the amplitude ratios characterizing g_0, the tension between theory and experiment occurs at levels of 0.3% to 3.0% for several universality classes. This is illustrated in Table 2 with recent values of α from several sources for the d = 3, n = 1 class.

The subdominant critical exponent (Δ) and the amplitude ratios characterizing g_1 are not known nearly as well

Table 2 Recent values of the specific heat exponent, α, for d = 3, n = 1

System	Value of α	Reference
Renormalization group	0.1098 ± 0.0024	20
Body-centered cubic Ising model	0.1066 ± 0.0009	21
Liquid-vapor (CO_2)	0.1084 ± 0.0023	8
Binary liquid mixture (triethylamine-D_20)	0.107 ± 0.002	22

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from experiments. There the uncertainties are, roughly speaking, 10% to 50% for the best experiments. Often the data are precise; however, there is no general agreement on which questions are to be asked of data, and the issue of the relationship between laboratory variables and the abstract fields becomes acute as one moves away from the critical point.

Other Phenomena of Current Theoretical Interest

For transport properties, the static universality classes have been subdivided according to the presence or absence of conservation laws for density variables.[23] The predictions for each class include the frequency and wave-vector (q) dependence of the transport property anomalies asymptotically close to critical points. In the hydrodynamic (zero wave-vector) limit, they are expected to show scaling behavior as a function of the correlation length and therefore as a function of the thermodynamic variables. For the fluids of concern here, the viscosity (η) is predicted[24] to show a weak divergence ($\eta \propto |t|^{-y}$, with $y \approx 0.033$). The fluctuations of the order parameter relax diffusively. The thermal diffusivity (D_T) of liquid-vapor systems and the mutual diffusion coefficient (D) of binary liquid mixtures both approach zero at critical points because of the diverging correlation length and the diverging viscosity

$$D \propto D_T \propto (\xi \cdot \eta)^{-1} \propto |t|^{\nu+y} \propto |t|^{0.63+0.03} \qquad (9)$$

When the wave-vector dependence of the transport properties is considered, scaling as a function of $q\xi$ has been predicted and confirmed[25-27] by experiment. The relevant experiments measure a dynamic scaling function, an exponent related to the viscosity exponent (y), and an amplitude ratio. Thus, the theoretical and experimental situation for transport properties closely resembles that for thermodynamic quantities. However, there is some doubt that the transport properties can be expanded in a form analogous to Eq. (4) in an experimentally meaningful regime. In Eq. (4), the anomalous terms are added to an analytic term and the first correction term differs from the leading term by an exponent $\Delta \approx 0.5$. Theoretically guided representations of the viscosity anomaly near critical points have used a multiplicative form for the anomaly without a correction term.[25,26]

For the transport properties, the tension between theory and experiment occurs at a 10% level[25] (for the exponent y and a particular dynamic amplitude ratio R).

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The nature of the correction terms (or, equivalently, "crossover functions") for the transport properties is not well-known.

There are several subjects of current interest for which both theory and experiment are much less developed. Because these subjects are less well developed, it is harder to argue that gravitational effects limit experimental progress. These subjects include the nature of the interface between coexisting critical phases,[28,29] the nature of the interface between a critical phase and a noncritical phase,[30] the sequence of events that control how a fluid system separates from one phase into two phases after a quench,[31-32] the sequence of events that controls the remixing of two phases into one phase after an inverse quench,[33,33a] the effects of laminar[34] and turbulent[35] flows on the structure of fluids, and the amplitude ratios[36] relating the interfacial tension between coexisting critical phases to bulk thermodynamic properties.

Equilibration and the Role of Fluid Systems in Testing Theory

The RG picture of bulk critical phenomena has been tested by experiments on systems representing many different universality classes including some systems[37,38] with d = 2, a few exactly solvable models, and approximate calculations on a wider range of models (notably, series expansions of the partition function of various Ising models and simulations of more complicated models). The general picture is confirmed in a remarkably wide range of cases. Nevertheless, the numerical quantities that are calculated within the RG picture always are calculated approximately. Thus, one can adopt the conservative point of view that a more accurate measurement of, for example, a critical exponent is a test of the approximations made in specific calculations and a challenge to improve the calculations. A more radical point of view would be that a more accurate measurement is required to find the limits of validity of a theoretical approach that claims to be fundamental and general. In either case, the experimentalist is challenged to improve the precision of measurement and to extend the range of measurements toward the critical point. (Of course, the same challenge is presented to those theorists who analyze specific lattice models.)

There is no doubt that the superfluid (lambda) transition in ^{4}He is the best experimental system for the accurate measurement[39] of the critical exponent α (which characterizes the divergence of C_V). The unique feature

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of ^{4}He is the rapid thermal equilibration of macroscopic samples, even very near the lambda transition. Other fluid systems can probe aspects of the theory that are not accessible to ^{4}He because the order parameter for the superfluid transition is not physically observable. For example, other fluid systems can be used for measurements of the correlation length via light scattering, the relaxation of order-parameter fluctuations in equilibrium, the response of the order parameter to external fields (such as gravity), the interfacial tension between coexisting phases, and the dynamics of the phase-separation process. In principle these latter quantities could be observed in solid systems with critical points; however, it is not possible to attain thermal equilibrium in a conveniently large sample of a solid on a laboratory time scale.

Near a critical point, a sample of material must have dimensions that exceed ξ in each direction if the sample's properties are to be representative of the properties of a bulk (infinite) sample. Thus, one can define a time, τ, that is required for a volume of fluid ξ^3 to attain equilibrium

$$\tau \equiv \xi^2/D = (\xi_0 t^{-\nu})^2/(D_0 t^{\upsilon+y}) = \tau_0 t^{-3\nu-y} \approx \tau_0 t^{-1.93} \quad (10)$$

D is replaced with D_T for liquid-vapor systems. Light-scattering data from the literature (see Refs. 27, 40, and 41) were used to estimate this local equilibration time, τ, at $t = 10^{-6}$ as well as the time, $\tau_{mm} \equiv (1\ mm)^2/D$, for equilibration of a 1 mm^3 sample at $t = 10^{-6}$ of some fluid systems. These estimates are listed in Table 3. Xenon (Xe) and ^{3}He are considered at liquid-vapor critical points and Me-Cy is the binary liquid mixture methanol-cyclohexane near its consolute point. Table 3 shows that at $t = 10^{-6}$, local equilibrium can be reached via diffusion on a convenient time scale; however, equilibrium cannot be attained in a volume of 1 mm^3 without waiting days. This condition greatly constrains measurements that might be carried out at $t = 10^{-6}$. For example, if a fluid sample ever were to become spatially inhomogeneous by spending some time below the critical temperature, stirring would be absolutely essential for remixing the fluid. (The shear flows associated with stirring decay rapidly. The energy required for mixing on large scales is negligible.) The entry τ_{mm} in Table 3 above refers to a homogeneous sample at the critical density. In Earth's gravitational field at $t = 10^{-6}$ most of a liquid-vapor sample 1 mm high is at least several percent above or below the critical density, and such a stratified sample relaxes much more rapidly.

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Table 3 Equilibration times for various systems

System	D_0 (in cm^2/s)	ξ_0 (in nm)	τ_0 (in s)	$\tau_0(10^{-6})^{-1.93}$ (in s)	τ_{mm} (in s)
Xe	5.1×10^{-4}	0.19	0.7×10^{-12}	0.27	1.9×10^{5}
^{3}He	1.5×10^{-4}	0.26	4.6×10^{-12}	1.70	6.8×10^{5}
Me-Cy	0.2×10^{-4}	0.35	53.0×10^{-12}	20.00	43×10^{5}

In contrast with fluid systems, solid systems cannot be homogenized by stirring. Lattice defects such as vacancies, interstitials, and dislocations effectively are frozen in place. Intuitively, one can view a macroscopic solid sample as a collection of samples, each with its own average lattice constant, critical temperature, and so forth. A macroscopic probe averages over such a collection of samples. (In some ways it is better to view the frozen defects as generating a randomly placed set of fields that couple to the order parameter and prevent the macroscopic sample from attaining the state h = 0.) In practice, the closeness of approach to the critical points in solids is limited by averages over such inhomogeneities.

Gravity Effects on Fluid Systems

There are two distinct roles that gravity plays in experimental studies of equilibrium critical phenomena. In the first role, gravitational stratification of fluids limits the resolution of measurements of fluid properties near critical points. In this role, gravity complicates experiments; however, it does not alter the phenomena under study. In its second role, gravity suppresses the fluctuations that would occur at the critical point in the absence of gravity. This second role can be described as an intrinsic limitation of experiments by gravity. Here, gravity affects fluids in the same way as lattice imperfections affect solids. Finally, the role of gravity in nonequilibrium phenomena is mentioned.

In Earth's gravitational field, the equilibrium density of a fluid decreases as a function of the vertical coordinate z. Under ordinary conditions, this stratification effect is so small that it is neglected. (At ambient temperature $[\partial\rho/\partial z]/\rho$ is 5×10^{-9}/mm for liquid water and 7×10^{-8}/mm for water vapor). As the critical point is approached, along the path of two-phase coexistence (the vapor-pressure curve), the symmetrized isothermal compressibility, $\chi_T = (\partial\rho/\partial\mu)_T$, diverges as $t^{-\gamma}$, where $\gamma \approx$

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1.24. The divergence in χ_T enormously magnifies this stratification. Values of $(\partial\rho/\partial z)/\rho$ of 0.1/mm are attained readily.

All experimental probes average the property they measure over a finite height. Near the liquid-vapor critical point, the errors that result from averaging over the height-dependent density can be the dominant ones. Moldover et al.[42] systematically estimated the experimental consequences of density averaging. They assumed that the local chemical potential $\mu[\rho(z),T]$ at each level, z, was equal to the chemical potential of a uniform fluid (that is, in a zero-gravity environment) at the same values of ρ and T. In this approximation, the density-versus-height profile can be obtained from the relation

$$\mu[\rho(z),T] - \mu[\rho(z_0),T] = -g_0 \cdot (z - z_0) \qquad (11)$$

Here, z_0 is a reference height that was chosen so that $\rho(z_0) = \rho_c$; g_0 is the acceleration due to Earth's gravity, 9.8 m/s^2; and $\mu(\rho,T)$ was obtained from an equation of state similar to that obtained by differentiating Eq. (4). Moldover et al. have shown that the effect of density averaging is to limit the effective temperature resolution of experiments to Δt_{min} and that Δt_{min} scales as $(g \cdot \underline{h}/H)^p$, where $\underline{h}$ is the height over which the experiments average, H is a system-dependent scale height that varies from 7 km for steam to 0.7 km for ^{3}He, and p is a combination of the universal exponents. Representative results for Xe are listed in Table 4. The tabulated values of Δt_{min} have been achieved in Earth-bound experiments in various fluids (not necessarily Xe).

The second class of equilibrium gravity effects are those that are independent of instrumentation. The properties of the fluids are altered by the presence of the gravitational field. In this context, gravity affects a liquid-vapor system near its critical point in the same way that an external magnetic field affects a magnetic solid near a Curie point. The external field prevents the experimental system from reaching the point $\tau = 0$, $h = 0$ in a finite-sized volume.

The importance of this external field can be estimated by asking when the gravitational contribution to the potential energy of a fluctuation becomes comparable to $k_B T_c$. The mean square fluctuations in the number of molecules in a volume, V, is given by

$$\langle (\Delta N)^2 \rangle = k_B T \cdot \chi_T \cdot V/m^2 \qquad (12)$$

where m is the molecular mass. The gravitional contribu-

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Table 4 Limits to measurements due to stratification

Measurement	Height	Δt_{min}	p
Coexisting densities via capacitance	0.2 mm	3×10^{-5}	0.81
Compressibility via capacitance	0.2 mm	7×10^{-5}	0.64
Specific heat	1 mm	3×10^{-5}	0.64
Equation of state via interferometry	3 mm (cell width)	3×10^{-5}	0.36
Correlation length	0.1 mm	3×10^{-5}	0.64

tion to the potential energy of a fluctuation of volume ξ^3 is equal to k_BT when

$$m \cdot g \cdot \xi \cdot < (\Delta N)^2 >^{1/2} = k_BT \qquad (13)$$

When χ_T and ξ are expressed as power laws on the path $h = 0$ and are inserted into this condition to define $t_{intrinsic}$ we obtain

$$t_{intrinsic} = 4 \times 10^{-7} \cdot (g/g_0)^{0.46} \qquad (14)$$

Density fluctuations cannot continue to grow when $|t|$ is reduced below $t_{intrinsic}$ because the gravitational contribution to the potential energy would exceed k_BT. Detailed calculations by Sengers and van Leeuwen[43,43a] confirm the order-of-magnitude estimate and the exponent in Eq. (14).

The state-of-the-art of temperature control readily can reach $t_{intrinsic}$. Unfortunately, the fluctuations are suppressed only within a volume that is about a correlation length in height (4 μm at $t_{intrinsic}$ for Xe). Presently, it is not possible to measure the properties of interest in such a small volume of fluid when the volume is part of a larger volume of near-critical fluid. (If such a small volume were studied in a small container by itself, the van der Waals forces exerted by the container walls on the fluid would produce effects that are comparable to gravity.)

In equilibrium, Earth's gravitational field suppresses long wavelength fluctuations of fluid interfaces in essentially the same way that it suppresses density fluctuations in a near-critical fluid. This is not a critical-point effect; however, it probably can be studied best by using fluids near a critical point and varying the degree of density matching between coexisting phases by isotopic substitution.

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When a fluid is forced out of equilibrium, for example, by quenching it from a one-phase state into a two-phase state, gravitational forces drive hydrodynamic flows that dominate the latter stages of phase separation. It has been shown by simple dimensional arguments that the earlier stages of phase separation are controlled first by diffusion and then by surface-tension-driven flows. (Flows driven by temperature gradients have not been considered.) In principle, a low-gravity environment would provide the opportunity to study the surface-tension-driven flows on a longer time scale and on a larger size scale than on Earth. This opportunity probably cannot be exploited using standard optical techniques. When the phase-separation process reaches these late stages in which the characteristic size of the emerging phases is comparable to or exceeds the wavelength of light, fluids become extremely turbid. Multiple scattering prevents the useful interpretation of data taken on conveniently sized samples.[44] If a thin sample were used, the presence of boundaries would influence the phase-separation process. An interesting system in which to study phase separation might be a ternary-liquid mixture chosen so that its coexisting phases near a consolute point have nearly identical indices of refraction. In such a system, one could simultaneously reduce multiple scattering and gravitationally driven flows (by working in a low-gravity environment).

The late stages of phase separation of a fluid system near a critical point are not essentially different from the late stages of phase separation of a fluid system far away from a critical point. In both cases, the phenomena are controlled by hydrodynamics. The proximity to the critical point merely determines the values of thermodynamic and transport properties that are to be substituted into the hydrodynamic equations. (In this context, "late stages" probably means at times greater than τ as defined by Eq. [10].)

Representative Low-Gravity Experiments

This section describes four planned low-gravity measurements in the area of critical phenomena. Two are being led in Europe and are in advanced stages of development. The other two are in earlier stages of development in the U.S. and directly involve the author.

Of the four experiments, only the one developed by Dr. Beysens and his co-workers (CEN, Saclay, France) could possibly be considered a qualitative "look-and-see" experiment. Beysens has been studying the phase separation of binary liquid mixtures of Me and Cy.[45,46] The

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coexisting phases of this mixture are, by accident, very nearly density matched ($\Delta\rho \approx 0.0026$ gm/cm^3 $\cdot$ $(-t)^{0.33}$ from Ref. 36). Beysens has improved the density match by substituting deuterated Cy for normal Cy. The deuteration was continued until the capillary length for the interface between the coexisting phases was increased to 1 cm when $t \approx 10^{-4}$. From measurements of the interfacial tension, one would expect that this criterion achieves a density match of the coexisting phases to much better than 1 part in 10^6 at the prescribed temperature. Beysens reports that difficulties in controlling the concentration of an impurity (water) actually limited the accuracy of the density match to 1 part in 10^6. Such a density-matched sample was observed to separate into distinct phases on Earth in less than 5 min after being quenched from $t = 1.7 \times 10^{-5}$ to $t = -3.4 \times 10^{-5}$ in a container 1.0 cm high and 0.2 cm thick. The later stages of the phase separation are accompanied by convective motion. A similarly sized sample that was not as carefully density matched showed no evidence (in a high-resolution movie) of any phase separation after being quenched in a sounding rocket and left undisturbed in a 10^{-6} g environment for 6 min.[46] The movie made during the flight simply showed a totally turbid, fluctuating sample whose properties did not change. These preliminary results have not been explained. Beysens is planning similar experiments of longer duration in the European Spacelab.

Professor Straub and co-workers[47] at the Technical University of Munich are planning to measure the exponent α, characterizing the constant-volume specific heat divergence near the critical point of sulfur hexafluoride. An Earth-based version of his experiment has demonstrated roughly 1% resolution in C_v in the temperature range $10^{-6} < |t| < 3 \times 10^{-4}$. When $|t| < 5 \times 10^{-5}$, the resolution of the measurement is limited by the stratification of the 1-mm-high sample in the Earth's gravitational field. This experiment apparently does not include provision for stirring. Thus, one might speculate that incomplete temperature equilibration will limit the resolution of this experiment in a low-gravity environment. (The apparent resolution of heat-capacity measurements of both one-phase and two-phase states of binary liquid mixtures on Earth is known[22] to be greatly enhanced by moderate controlled stirring. Presumably this occurs because the macroscopic equilibration time begins to approach the local equilibration time.)

One can use Eq. (8) to estimate the precision with which Straub's experiment can determine the value of α. If the desired temperature resolution is indeed achieved,

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Straub's experiment will span approximately two decades in t where $t^{\Delta} < 10^{-2}$. Thus the experiment will determine α with a precision near 2%. This precision is comparable to the precision that has been obtained on Earth when C_V was measured with higher resolution outside the gravity-limited range.[8] Presumably, in future versions of Straub's experiment, higher resolution techniques will be adopted. The present version of Straub's experiment was scheduled to be flown in October 1985 on the European Spacelab.

Professor Gammon[48,48a] and co-workers at the University of Maryland have designed a low-gravity experiment to measure the correlation length and the decay rate of density fluctuations much closer to the critical point of Xe than is possible with any Earth-based experiment. The primary scientific objective of Gammon's experiment is to test the theory for the decay of density fluctuations in the nonhydrodynamic limit. The limits $t \to 0$ and $h \to 0$ have to be achieved as well as the limit $q\xi >> 1$.

To establish the feasibility of the optical aspects of this experiment, Gammon demonstrated,[44,48,48a] with a density-matched binary liquid mixture, that multiple scattering could be avoided by using an optical cell with a path length only 200 μm long. A small, light, multistage thermostat was demonstrated to control the temperature of a fluid sample to a few parts in 10^8. The thermostat responds to small changes in set point in less than 5 min, and it responds to major changes, where all stages are reset, in less than 45 min. Thus, data at many temperatures can be acquired during a normal shuttle mission. Many other problems had to be overcome during this experiment. Gammon demonstrated the capability for loading the sample cell with a mixture within 0.05% of the critical composition, precisely measuring the critical temperature, accurately measuring the scattering angles, accurately measuring the decay rate of fluctuations from a thin sample without interference from window scattering and minimizing fractionation of the sample by the formation of wetting layers on the walls of the sample cell. This list of problems underlines that this is a very sophisticated experiment that has been developed with man-years of ground-based research. The specifications for the low-gravity version of this experiment now are in preparation.

The author has been developing a related experiment to measure the divergence of the shear viscosity in the hydrodynamic limit near the critical point of Xe. The conditions $h \to 0$ and $t \to 0$ must be achieved as well as the dynamic conditions $\omega\tau < 1$ and $S\tau < 1$. Here, τ is the local equilibration time defined by Eq. (10) above and tabulated

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earlier, ω is the angular frequency of the viscosity measurement, and S is the maximum shear rate used in the viscosity measurement. It is possible to approach the condition $\omega = 0$ by using, for example, a capillary-flow viscometer; however, such viscometers typically have a value of S near 100 s^{-1}. In collaboration with Dr. R. Berg, the author has developed a novel "cup" viscometer that contains a fluid sample within a cylindrical container, which also acts as the inertial element of a torsion oscillator. The damping of the oscillator is used to measure the viscosity. This instrument has been used to measure the viscosity of binary mixtures of Me and Cy with a precision of $\pm 0.2\%$ in the range $10^{-5} < t < 10^{-2}$, while maintaining the very low values $S = 0.5\ s^{-1}$ and $\omega = 3$ rad/s. These preliminary data[49] lead to the value of the viscosity exponent $y = 0.041 \pm 0.001$. This value clearly disagrees with two recent calculations[24] that yield $y = 0.033$.

This viscosity apparatus is being tested with liquid-vapor systems on Earth. Gravitational stratification of liquid-vapor systems is expected to limit the use of this novel viscometer to the range $t > 10^{-4}$. A low-gravity experiment with Xe could extend the useful range to $t = 10^{-6}$, where violations of the condition $\omega\tau < 1$ begin. (Density-matched binary mixtures are not totally satisfactory substitutes for a liquid-vapor system because they relax more slowly, limiting the hydrodynamic regime to $t > 10^{-5}$, and because the separation of the viscosity into critical and noncritical parts is more complicated.)

The ultimate objective of both the light-scattering and viscosity experiments is to combine their data to test the mode-coupling theory near the critical point with the fewest possible assumptions. In its present form, this theory leads to a pair of coupled integral equations over particular functions of the static structure factor. The equations relate the wave-vector-dependent fluctuation corrections to the shear viscosity to the fluctuation-decay rates observed optically. It follows that a test of the theory with the fewest possible assumptions also will require viscosity data in the nonhydrodynamic region, $\omega\tau \gg 1$. The possibility of combining such high-frequency measurements with present measurements in the hydrodynamic regime is under study.

Opportunities for Academic Research in a Low-Gravity Environment

Of the four experiments that have been described above, two are being conducted in an academic environment and the other two are being carried out in government

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laboratories, which have much in common with an academic environment. The development of the viscometer at the National Bureau of Standards has involved the full-time effort of one postdoctoral research associate and the part-time effort of a senior staff member for 2 years. The expenditures for such things as capital equipment, supplies, travel, and publication costs, have been commensurate with the expenditures for such items by a research project involving one postdoctoral associate at an academic institution.

It is anticipated that this level of effort will continue for 1 more year, at which time the parameters of the low-gravity version of the experiment will have been fully defined. After that, substantial engineering assistance will be required to develop the low-gravity version of the experiment.

In addition to the four projects just described, there are other opportunities for exploiting low-gravity environments for the study of critical phenomena. Obviously, detailed study of the static anomalies other than C_v also could profit from a low-gravity environment. Other opportunities involve looking for weak effects that are either comparable in scale to a fluid's response to gravity or effects that are swamped entirely by a fluid's response to gravity. An example is the experimental search for a dielectric constant anomaly near a liquid-vapor critical point. Several spurious reports of such an anomaly have resulted from unrecognized effects of gravitational stratification.[50] The spurious anomalies were much bigger than order-of-magnitude estimates for the theoretically expected anomaly. Another weak effect is a fluid's response to the van der Waals forces between the fluid and a nearby solid, such as a container wall. In some circumstances, wetting layers form on a wall, and their thickness is controlled by the competition between gravity and the long-ranged van der Waals forces.[51] In a low-gravity environment, such layers are expected to be much thicker. Beysens has suggested[45] that the study of such layers would be assisted by a low-gravity environment.

Discussions of opportunities for low-gravity research in critical phenomena frequently conclude by recommending a simple photographic study of a phase-separating pure fluid near its critical point, perhaps along the lines of Beysens' work with binary mixtures.[52] If multiple scattering were overcome, such a study would reveal ordinary hydrodynamic phenomena albeit in a fluid with an extraordinary high Prandtl number. Thus, the merits of such a photographic study should be argued in the context of its contributions to understanding hydrodynamics rather than its contributions to understanding critical phenomena.

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References

[1]Griffiths, R.B. and Wheeler, J.C., "Critical Points in Multicomponent Systems," Phys. Rev., Vol. A2, 1970, pp. 1047-1064.

[2]Ley-Koo, M. and Green, M.S., "Consequences of the Renormalization Group for the Thermodynamics of Fluids Near the Critical Point," Phys. Rev., Vol. 23A, 1981, pp. 2650-2659.

[3]Moldover, M.R., "Thermodynamic Anomalies Near the Liquid-Vapor Critical Point: A Review of Experiments," Phase Transitions: Cargese 1980, edited by M. Levy, J.C. Le Guillou, and J. Zinn-Justin, Plenum, NY, 1982, pp. 63-94.

[4]Balfour, F.W., Senger, J.V., Moldover, M.R., and Sengers, J.M.H. Levelt, "A Revised and Extended Scaled Equation of State for Steam in the Critical Region," Proceedings of the Seventh Symposium on Thermophysical Properties, edited by A. Cezairliyan, American Society of Mechanical Engineers, NY, 1977, pp. 786-793.

[5]Wegner, F.J., "Corrections to Scaling Laws," Phys. Rev., Vol. 5B, 1972, pp. 4529-4536.

[5a]Wegner, F.J., "Critical Exponents in Isotropic Spin Systems," Phys. Rev., Vol. 6B, 1972, pp. 1891-1893.

[6]Moldover, M.R., "Scaling of the Specific-Heat Singularity of ^{4}He Near its Critical Point," Phys. Rev., Vol. 182, 1969, pp. 342-353.

[7]Hocken, R. and Moldover, M.R., "Ising Critical Exponents in Real Fluids: An Experiment," Phys. Rev. Lett., Vol. 37, 1976, pp. 29-32.

[8]Edwards, T.J., "Specific Heat Measurements Near the Critical Point of Carbon Dioxide," Ph.D. Thesis, University of Western Australia, Australia, 1984.

[9]Lipa, J.A., Edwards, C., and Buckingham, M.J., "Specific Heat of CO_2 Near the Critical Point," Phys. Rev., Vol. A15, 1977, pp. 778-789. (These data have been reanalyzed in Ref. 3.)

[10]Balzarini, D. and Mouritsen, O.G., "Universal Ratio of Correction-to-Scaling Amplitudes for Xe," Phys. Rev., Vol. A28, 1983, pp. 3515-3519.

Downloaded by RMIT BUNDOORA LIBRARY on August 15, 2015 | http://arc.aiaa.org | DOI: 10.2514/4.865824

AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[11]Pestak, M.W. and Chan, M.H.W., "Equation of State of N_2 and Ne Near Their Critical Points. Scaling, Corrections to Scaling, and Amplitude Ratios," Phys. Rev., Vol. B30, 1984, pp. 274-288.

[12]Guttinger, H. and Cannell, D.S., "Corrections to Scaling in the Susceptibility of Xenon," Phys. Rev., Vol. A24, 1981, pp. 3188-3201.

[13]Guttinger, H. and Cannell, D.S., "Correlation Range and Rayleigh Linewidth of Xenon Near the Critical Point," Phys. Rev., Vol. A22, 1980, pp. 285-286.

[14]Aharony, A. and Hohenberg, P.C., "Universal Relations Among Thermodynamic Critical Amplitudes," Phys. Rev., Vol. B13, 1976, pp. 3081-3090.

[15]Hohenberg, P.C., Aharony, A., Halpering, B.I., and Siggia, E.D., "Two-Scale-Factor Universality and the Renormalization Group," Phys. Rev., Vol. B13, 1976, pp. 2986-2996.

[16]Stauffer, D., Ferer, M., and Wortis, M., "Universality of Second-Order Phase Transitions: The Scale Factor for the Correlation Length," Phys. Rev. Lett, Vol. 29, 1972, pp. 345-349.

[17]Sengers, J.V. and Moldover, M.R., "Two-Scale-Factor Universality Near the Critical Points of Fluids," Physics Letters, Vol. 66A, 1978, pp. 44-46.

[18]Beysens, D., Bourgou, A., and Calmettes, P., "Experimental Determinations of Universal Amplitude Combinations for Binary Fluids, I. Statics," Phys. Rev., Vol. A26, 1982, pp. 3589-3609.

[19]Sengers, J.V. and Sengers, J.M.H. Levelt, "A Universal Representation of the Thermodynamic Properties of Fluids in the Critical Region," Int. J. Thermophysics, Vol. 5, 1984, pp. 195-208.

[20]Le Guillou, J.C., and Zinn-Justin, J., "Critical Exponents from Field Theory," Phys. Rev., Vol. B21, 1980, pp. 3976-3998.

[21]George, M.J. and Rehr, J.J., "Two-Series Approach to Partial Differential Approximants: Three-Dimensional Ising Models," Phys. Rev. Lett., Vol. 53, pp. 2063-2066.

[22]Bloemen, E., Thoen, J., and Van Dael, W., "The Specific Heat Anomaly in Triethylamine-Heavy Water Near the Critical Solution Point," J. Chem. Phys., Vol. 73, 1980, pp. 4628-4634.

[23]Hohenberg, P.C. and Halperin, B.I., "Theory of Dynamic Critical Phenomena," Rev. Mod. Phys., Vol. 49, 1977, pp. 435-479.

[24]Bhattacharjee, J.K. and Ferrell, R.A., "Critical Viscosity Exponent for a Classical Fluid," Phys. Rev., Vol. A28, 1983, pp. 2363-2369.

[25]Sengers, J.V., "Transport Properties of Fluids Near Critical Points," Int. J. Thermophysics, Vol. 6, 1985, pp. 203-232.

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AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[26]Burstyn, H.C., Sengers, J.V., Bhattacharjee, J.K., and Ferrell, R.A., "Dynamic Scaling Function for Critical Fluctuations in Classical Fluids," Phys. Rev., Vol. A28, 1983, pp. 1567-1578.

[27]Swinney, H.L. and Henry, D.L., "Dynamics of Fluids Near the Critical Point: Decay Rate of Order-Parameter Fluctuations," Phys. Rev., Vol. A8, 1973, pp. 2586-2617.

[28]Jasnow, D., "Critical Phenomena at Interfaces," Rep. Prog. Phys., Vol. 47, 1984, pp. 1059-1132.

[29]Jasnow, D. and Rudnick, J., "Interfacial Profile in Three Dimensions," Phys. Rev. Lett., Vol. 41, 1978, pp. 698-701.

[30]Ramos-Gomez, F. and Widom, B., "Noncritical Interface Near a Critical End Point II," Physica, Vol. 104A, 1980, pp. 595-620.

[31]Kim, M.W., Schwartz, A.J., and Goldburg, W.I., "Evidence for the Influence of Hydrodynamics in a Phase-Separating Fluid," Phys. Rev. Lett., Vol. 41, 1978, pp. 657-660.

[31a]Joshua, M. and Goldburg, W.I., "Periodic Spinodal Decomposition in a Binary Liquid Mixture," Phys. Rev., Vol. 31, 1985, pp. 3857-3867.

[32]Siggia, E.D., "Late Stages of Spinodal Decomposition in Binary Mixtures," Phys. Rev., Vol. A20, 1979, pp. 595-605.

[33]Easwar, N., Maher, J.V., Pine, D.J., and Goldburg, W.I., "Active-Coupling Mixing Times for a Stirred Binary Liquid," Phys. Rev. Lett., Vol. 51, 1983, pp. 1272-1274.

[33a]Chan, C.K., Maher, J.V., and Goldburg, W.I., "Active-Coupling Mixing Times for a Stirred Binary Liquid," Phys. Rev., Vol. 32A, 1985, p. 3117.

[34]Beysens, D., Gbadamassi, M., and Moncef-Bouarz, B., "New Developments in the Study of Binary Fluids Under Shear Flow," Phys. Rev., Vol. A28, 1983, pp. 2491-2509.

[35]Satten, G. and Ronis, D., "Critical Phenomena in Randomly Stirred Fluids," Phys. Rev. Lett., Vol. 55, 1985, pp. 91-94.

[36]Moldover, M.R., "Interfacial Tension of Fluids Near Critical Points and Two-Scale-Factor Universality," Phys. Rev., Vol. A31, 1985, pp. 1022-1033.

[37]Kim, H.K. and Chan, M.H.W., "Experimental Determination of a Two-Dimensional Liquid-Vapor Critical-Point Exponent," Phys. Rev. Lett., Vol. 53, 1984, pp. 170-173.

[38]Campuzano, J.C., Foster, M.S., Jennings, G., Willis, R.F., and Unertl, W., "Au(110) (1x2)-to-(1x1) Phase Transition: A Physical Realization of the Two-Dimensional Ising Model," Phys. Rev. Lett., Vol. 54, 1985, pp. 2684-2687.

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AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics

[39]Lipa, J.A. and Chui, T.C., "Very High-Resolution Heat-Capacity Measurements Near the Lambda Point of Helium," Phys. Rev. Lett., Vol. 51, 1983, pp. 2291-2294.

[40]Miura, Y., Meyer, H., and Ikushima, A., "The Decay Rate of Critical Fluctuations in ^{3}He-^{4}He Mixtures Near the Gas-Liquid Critical Point," J. Low Temp. Phys., Vol. 55, 1984, pp. 247-271.

[41]Kopelman, R.B., "Light Scattering Measurements of Critical Fluctuations in an Optically Thin Binary Liquid Sample," Ph.D. Thesis, University of Maryland, College Park, MD, 1983.

[42]Moldover, M.R., Sengers, J.V., Gammon, R.W., and Hocken, R. J., "Gravity Effects in Fluids Near the Gas-Liquid Critical Point," Rev. Mod. Phys., Vol. 51, 1979, pp. 79-99.

[43]Sengers, J.V. and van Leeuwen, J.M.J., "Critical Phenomena in Gases in the Presence of Gravity," Int. J. Thermophysics, Vol. 6, 1985, pp. 545-559.

[43a]van Leeuwen, J.M.J. and Sengers, J.V., "Gravity Effects on the Correlation Length in Gases Near the Critical Point," Physica, Vol. 128A, 1984, pp. 99-131.

[44]Moldover, M.R. and Gammon, R.W., "Conceptual Design of Low Gravity Experiments on Phase Transition and Critical Phenomena in Fluids," NASA CR-174637, 1983.

[45]Houessou, C., Guenoun, P., Gastaud, R., Perrot, F., and Beysens, D., "Critical Behavior of the Binary Fluids Cyclohexane-Methanol, Deuterated Cyclohexane-Methanol and of Their Isodensity Mixture: Application to Microgravity Simulations and Wetting Phenomena," Phys. Rev. A, Vol. 32A, 1985, pp. 1818-1833.

[46]Beysens, D., private communication.

[47]Lange, R. and Straub, J., "Die Isochore Warmekapazitat Fluider Stoffe im Kritischen Gebiet Region Voruntersuchungen zu einem Spacelab Experiment," Bundesministerium fur Forschung und Technologie Report #BMFT-FB-W-84-034, Fach-Informations-Zentrum, Karlsruhe, FRG, Aug. 1984.

[48]Kopelman, R.B., Gammon, R.W., and Moldover, M.R., "Turbidity Very Near the Critical Point of Methanol-Cyclohexane Mixtures," Phys. Rev., Vol. A29, 1984, pp. 2048-2053.

[48a]Gammon, R.W., private communication.

[49]Berg, R. and Moldover, M.R., "Viscosity Measurements Near Critical Points Using a Novel Torsion Oscillator," Int. J. Thermophysics, in press.

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AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[50]Thijsse, B.J., "The Dielectric Constant of SF_6 Near the Critical Point," J. Chem. Phys., Vol. 74, 1981, pp. 4678-4692.

[51]Kayser, R.F., Schmidt, J.W., and Moldover, M.R., "Wetting Layers and Dispersion Forces for a Fluid in Contact With a Vertical Wall," Phys. Rev. Lett., Vol. 54, 1985, pp. 707-710.

[52]Moldover, M.R., Hocken, R.J., Gammon, R.W., and Senger, J.V., "Spacelab Experiment Definition Study on Phase Transition and Critical Phenomena in Fluids: Interim Report on Experimental Justification," National Bureau of Standards Tech. Note 925, U.S. Government Printing Office, 1976; also published as NASA CR-135070.

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Comments on Critical Phenomena

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This review reflects the perspective of an author whose expertise is in phase equilibrium in binary and ternary mixtures of fluids, and in equilibrium critical and tricritical phenomena in these systems. The author's opinions are based on his work more as an experimentalist rather than as a theoretician.

Why Low Gravity?

At a critical point T_c the partial derivative at constant temperature of the chemical potential μ with respect to an order parameter ψ, $(\partial\mu/\partial\psi)_T$, necessarily vanishes. Whatever the order parameter, it is coupled directly or indirectly with the density, so large gradients in the concentration or the density are produced in the critical region by gravitational effects. These gradients have unavoidable and undesirable consequences if one wants to study the behavior of systems extremely close to the critical point. That is, for very small values of the scaling parameter $t = (T-T_c)/T_c$), 1) only a single layer can be at the critical density or the critical concentration, and many measurements (e.g., of the heat capacity) necessarily average over the whole sample, and 2) the gradients in effect suppress the full range of fluctuations expected in the critical region. Obviously, if special problems associated with low gravity can be resolved, experiments under these conditions could yield information about behavior at very small t, perhaps as small as 10^{-9}--at least three orders of magnitude smaller than that presently attainable on Earth.

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Materials

The number of satisfactory fluid systems for study in space is extremely limited, particularly when one recognizes that one should use only those substances that already have been studied as exhaustively as possible on the ground.

First, there is helium (He), uniquely desirable because it can be made exceptionally pure and because it exists as a liquid and as a superfluid under conditions where an extraordinary degree of temperature control is possible and where different properties can be measured with very high precision. Moreover, He not only has the usual gas-liquid critical point (Ising-like, with the number of vector components n = 1), but also a lambda transition (n = 2) and a tricritical point in the mixture of He isotopes, ^{4}He + ^{3}He (with essentially classical or Landau-type behavior). However, at the lambda transition one cannot measure the order parameter, so it is impossible to determine the correlation length and related properties. Second, of the "classical" fluids, xenon (Xe) and sulfur hexafluoride (SF_6) have been suggested as good choices, Xe because it is a monatomic fluid, and SF_6 because its critical point occurs just above room temperature. Measurements with them have lots of problems that are avoidable with He.

Finally, it is doubtful that, at least at present, anything useful could be obtained from measurements of critical phenomena in binary mixtures (with the exception of the special case of the mixture of He isotopes). There are problems of mixing, and the establishment of equilibrium will be much slower; the time for the decay of fluctuations in concentration is at least an order of magnitude longer than for fluctuations in density (as Moldover shows in Chapter 2B). Moreover, there is no reason to believe that the critical behavior of multicomponent fluid mixtures is in any fundamental sense different from that of one-component (pure) fluids. There is no reason to pile up data on different systems when one expects to find no differences; it is much better to make very careful measurements on a few systems.

Equilibrium Properties

A great deal already is known about the thermodynamic behavior of fluids in the critical region from careful ground-based experiments, and no proposed experiment in space should be considered unless it offers the possibility of yielding information that is almost impossible to obtain on Earth.

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It appears that the equilibrium critical exponents for Ising-like fluids and fluid mixtures (i.e., n = 1), derived from theoretical power-series expansions, from renormalization group (RG) theory, and from experiment, are now in essentially complete agreement. Although it is true that some experiments are such that the data must be fit to the equations of "extended scaling" with several parameters, a few experiments are largely free of these complications, so the present author believes that Lipa's description of the situation (with the quotation from Guttinger and Cannell) is an overcautious statement, almost a misrepresentation, of the current situation (see Chapter 2A). In the opinion of the author, the Ising exponents are now sufficiently well established that experiments to determine them in space (or indeed further experiments on Earth) will be increasingly hard to justify.

The situation regarding the lambda transition in He is somewhat different. As Lipa emphasizes, there are still some residual discrepancies between theory and experiment for the n = 2 exponents, particularly the heat-capacity exponent α, and low-gravity experiments to resolve these can be performed with extremely high resolution. Unless the theoretical calculations for n = 2 have been determined less carefully than those for n = 1, the low-gravity experiments probably will show that the RG exponents are correct. Because these experiments appear to be capable of resolving the discrepancy (or of showing that it is real and that there are serious problems with RG theory), they are, of course, important to do. Moreover, it is very desirable to have at least one exponent value determined with such high precision that the theorists will have the motivation to refine their calculations further.

The precise determination of the heat-capacity exponent α for the lambda transition will have the additional dividend that, when combined with speed of sound measurements, it will yield a precise value for the superfluid density exponent ζ, which is identical to the correlation length exponent ν. This will then permit a test of the "hyperscaling" hypothesis that $d\nu = 2 - \alpha$ or, for the real world of three dimensions (d = 3), $\nu = (2 - \alpha)/3$.

There is still a real challenge to theoreticians here. All the experiments, at least for n = 1 fluids, indicate that the scaling hypothesis, which links the exponents, is correct within decreasingly small experimental error, and increasingly careful series expansions indicate the same conclusion, even for "hyperscaling." RG theory, of course, assumes scaling. The challenge is to show that scaling can be derived from the first principles of statistical mechanics or, if it cannot, to show what the nature and magnitude of the deviations are.

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Despite the availability of satisfactory Ising exponents, there is at least one area in which equilibrium measurements in space might still be interesting and important: the determination of the exact form of coexistence curves at a critical point or a tricritical point.

According to theory, the limiting form of the coexistence curve can be represented by two equations

$$\rho' - \rho'' = B\,|\,t\,|^{\beta} \tag{1}$$

and

$$\rho' + \rho'' = A + C|\,t\,|^{1-\alpha} + Dt \tag{2}$$

where ρ' and ρ'' are the densities of the coexisting phases, $t = (T-T_c)/T_c$; A, B, C, and D are constants; and α and β are the usual critical exponents. For Ising-like fluids (n = 1) and fluid mixtures, Eq. (1) is now well-confirmed by experiment, with the experimental β in excellent agreement with the RG value (0.325).

If C is set equal to zero, Eq. (2) reduces to the familiar "Law of the Rectilinear Diameter." However, for any nonzero C, no matter how small, the second term with its exponent 0.89 ultimately will, at sufficiently small t, dominate the third term with its larger exponent, 1, introducing curvature into the otherwise rectilinear diameter (Fig. 1). There is a little experimental evidence for this nonlinearity at small t, but it is far from conclusive. The interpretation of the experiments[1] that suggest a $(1-\alpha)$ term for SF_6 has been questioned,[2] and the analysis[3] of coexistence curves for binary mixtures cannot clearly

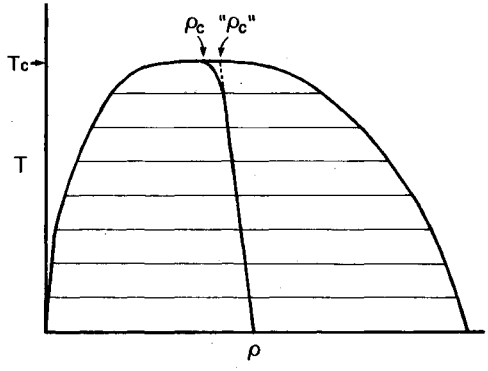

Fig. 1 Schematic diagram of fluid coexistence curve in the critical region, showing the expected curvature of the diameter as one approaches T_c. Note the difference between the linearly extrapolated critical density "ρ_c" and the true ρ_c. Not to scale.

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distinguish between the (1-α) term and the "2β-effect" that arises from a poor choice of order parameter.

Thus, a precise determination of the coexistence curve in the immediate vicinity of the gas-liquid critical point of a simple fluid would shed light on this remaining problem. Moreover, the resolution of this difficulty would have the nontrivial result of greatly improving the accuracy of the determination of critical densities and concentrations; at present, these are almost always evaluated by extrapolating a straight-line diameter to the critical temperature and thus could easily be wrong by as much as 1% (The solution of this problem may even have a feedback effect on other experiments in space that are supposed to be measured at the correct critical density.)

The coexistence curve in the vicinity of a tricritical point should have the classical exponent $\beta_2 = 1.00$ (i.e., the two branches of the phase boundary are straight lines that intersect at the tricritical point), and the symmetrical tricritical point in the mixture $^4He + {}^3He$ has been found experimentally[4] to agree (Fig. 2) with this prediction, at least to within less than one millikelvin of the tricritical point ($t = 10^{-3}$). However, because a dimensionality $d = 3$ is the point of crossover between classical and nonclassical behavior, one expects logarithmic corrections to the classical behavior if one gets sufficiently close to the tricritical point.

These corrections[5] should be manifest not in any markedly visible curvature of the phase boundary, but

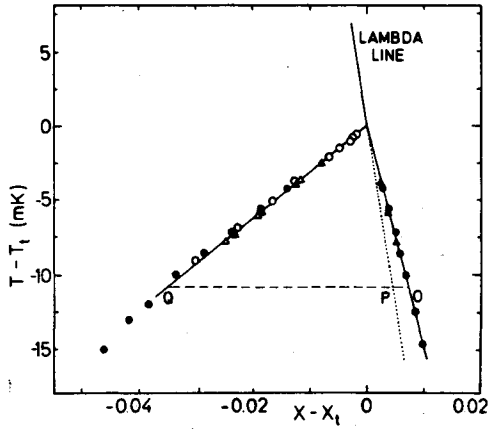

Fig. 2 The phase diagram for $^4He + {}^3He$ in the immediate vicinity of the tricritical point, showing the lambda line and the two branches of the coexistence curve as three straight lines. (Reproduced from Leiderer and Bosch, Ref. 4)

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rather by a slow decrease in the slopes of the two branches that should appear at very small t, over several decades in t. This is illustrated in Fig. 3, where the circles show the region blown up in the next lower diagram. (The rate of change of slope for the disordered (^{3}He-rich) phase should be much slower even than that of the ordered phase.) This predicted effect has not yet been observed in any fluid tricritical system. If the coexistence curve of ^{4}He + ^{3}He could be measured to microkelvin precision or better (i.e., $t \leq 10^{-6}$), this effect might be found.

These coexistence-curve experiments would not be easy. The determination of a phase diagram requires either the measurement of the difference in some property (e.g., refractive index or density) between coexisting phases or the measurement of a separation temperature for a series of samples of varying overall density or composition. Because in low gravity, segregation into macroscopically separated phases will be extremely slow, measurements on distinct coexisting phases (either in situ or by sampling) appear almost impossible.

The separation temperature of a sample can be determined by observing the change in character of the light scattering as one reaches the phase boundary from the one-phase region (critical opalescence and incipient nucleation are distinctly different). However, for "normal" fluids such as Xe or SF_6, the reproducible purity of the different samples becomes crucial as one enters the microkelvin region, and it would be equally crucial for the He mixture in the micro- or nanokelvin region. It may be impossible to exclude slight impurities when one prepares different samples of "pure" Xe. Because of the special properties of He (among them the feature that one expects any impurity to freeze out), it might be possible to prepare He mixtures of sufficient purity to look for these logarithmic corrections.

Nonequilibrium Properties

The theory of transport and other nonthermodynamic properties in the critical region is much less well developed than the theory of equilibrium properties. There are exponents associated with these, but they are less accurately determined either from theory or experiment than the thermodynamic ones. In some ways the experiments are more difficult to carry out, even on Earth, than the corresponding equilibrium ones. Moldover and Gammon have proposed experiments on viscosity and on dynamic light scattering, to be carried out in space, probably on

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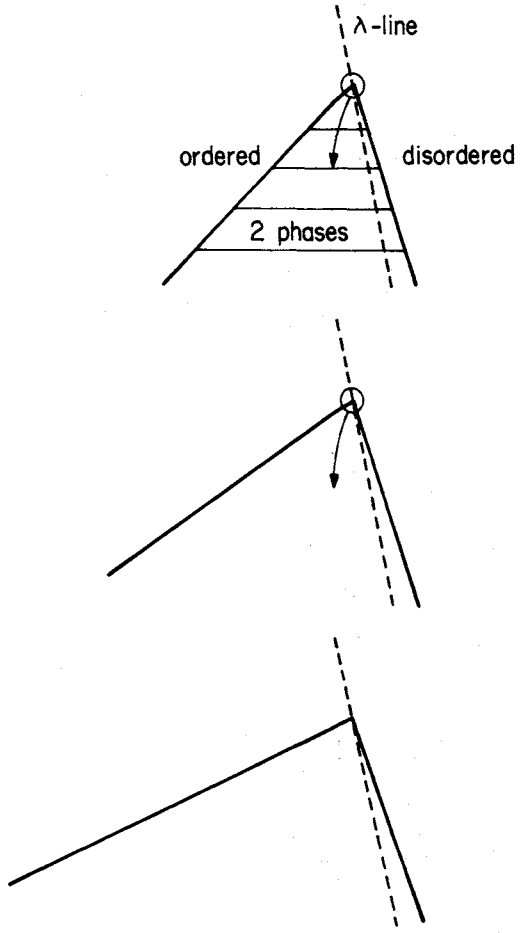

Fig. 3 Schematic representation of the predicted phase diagram for $^4He + {}^3He$, showing the slow decrease in slope of the coexistence curve as T_t is approached. Each successive diagram represents an enlargement of scale of more than a factor of 10.

Xe, and have simulated the low-gravity conditions by studying density-matched binary fluid mixtures (e.g., methanol + cyclohexane). To get the maximum information, the viscosity and the rate of decay of correlations must be measured on the same system. Note that studies of these binary systems on Earth are not a completely satisfactory substitute for actual studies on a one-component system in space for several reasons, among them: 1) as noted earlier, the equilibration times are so much longer for mixtures; and 2) exact density matching is possible only at a single temperature.

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Summary

Studies in space of equilibrium and nonequilibrium properties in the critical region, carefully designed to take maximum advantage of low-gravity conditions, offer the opportunity of extending our understanding of this field. Although the general "nonclassical" aspects of critical phenomena are now reasonably well understood, at least in a semiquantitative sense, sufficiently so that one does not expect any real scientific breakthroughs, the chance to "finish off" the subject by experiments in space is appealing.

References

[1]Weiner, J., Langley, K.H., and Ford, N.C., Jr., "Experimental Evidence for a Departure from the Law of the Rectilinear Diameter," Phys. Rev. Lett., Vol. 32, 1974, pp. 879-881.

[2]Moldover, M.R. and Gammon, R.W., "Capillary Rise, Wetting Layers, and Critical Phenomena in Confined Geometry," J. Chem. Phys., Vol. 80, 1984, pp. 528-535.

[3]Greer, S.C., Das, B.K., Kumar, A., and Gopal, E.S.R., "Critical Behavior of the Diameters of Liquid-Liquid Coexistence Curves," J. Chem. Phys., Vol. 79, 1983, pp. 4545-4552.

[4]Leiderer, P. and Bosch, W., "Universality of Tricritical ^{3}He-^{4}He Mixtures under Pressure," Phys. Rev. Lett., Vol. 45, 1980, pp. 727-729.

[5]Stephen, M.J., "Universality and Tricritical Points in Three Dimensions," J. Phys. C., Vol. 13, 1980, pp. L83-86.

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Gravity, Microgravity, and the Approach to Picogravity

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Background for Experimental Gravitation

In contemporary physics, experiments on gravitation --other than a measurement of the gravitational constant G or observations of a purely geophysical character--may be viewed ultimately as investigating either the assumptions or the consequences of Einstein's general theory of relativity. As such, they may be divided into three classes, depending on whether the effect under study influences a clock, a photon, or a massive body.

When Einstein formulated general relativity in 1915, he proposed three tests of the theory: 1) the gravitational redshift, 2) the deflection of starlight by the sun, and 3) detection of the relativistic term in the precession of the perihelion of the planet Mercury. The third test is an effect on a massive body, the second on a photon, whereas the first, which checks not so much a consequence of the theory as one of its assumptions, the strong equivalence principle, may be observed through either the change in wavelength of a photon or the change in rate of a clock resulting from a difference in gravitational potential. A fourth process, which Einstein identified but did not give any test for, was the propagation of gravitational radiation; this requires massive bodies for its detection.

The Einstein tests were observations of solar system or astrophysical phenomena rather than controlled experiments in the physicist's sense. During the 1950s and 1960s, a revived interest in gravitation led physicists to execute controlled experiments and suggest others. Two of the most noteworthy completed experiments were the ground-based measurement of gravitational redshift by Pound and Rebka[1] (later refined by Pound and Snider[1a]) and a greatly improved Eötvös experiment by Roll, Krotkov, and Dicke.[2] These two experiments test, respec-

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tively, what one would now call the "strong" and "weak" equivalence principles. Weak equivalence is the Galileo-Newton hypothesis of the universality of free fall, based on comparing the ratios of inertial to passive gravitational mass for bodies of different composition. Strong equivalence is Einstein's extension of the principle to all the laws of physics in freely falling frames, the redshift being one consequence of that extension.

Other important experiments from the 1960s related to gravity include Dicke and Kreuzer's ingenious demonstration of equivalence for active gravitational mass[3]; the controversial Dicke-Goldenberg[4,4a] measurement of the optical shape of the sun (which cast doubt on the earlier agreement between predicted and observed values for the relativistic contribution to the precession of the perihelion of Mercury); and the construction by Joseph Weber[5,5a] of the first gravitational wave antenna, the start of a 30-year search that may now be approaching fruition.

Meanwhile, two new realms for experimentation opened up: radio astronomy and space. Advances in planetary radar led Irwin Shapiro[6] in 1964 to suggest a new test of general relativity, the radar time delay experiment, a measurement of the relativistic increase in the roundtrip time for radar signals reflected from planets or spacecraft as they pass behind the sun. Measurements to the Mars-Viking Lander have now confirmed the predicted time delay to 0.1%, making this the most precise check of general relativity made so far.[7] A related development was the application of Very Long Baseline Interferometry (VLBI) to observe displacements between radio stars in the ecliptic plane on passing near the sun. These observations provide the first truly satisfactory check of the relativistic light deflection, now measured to 1%.[8,8a] The other new research realm from the 1960s, space, is the topic of the present chapter.

The Uses of Space in Gravitational Physics

Sputnik was launched in 1957. Physicists at once began thinking about the new opportunities for experiments on gravitation and relativity.[9,9a] Space offers the following four benefits:

- A change in gravitational potential with distance from Earth
- Microgravity (i.e., the reduced acceleration on an apparatus in free-fall)
- A cyclic change in direction of the gravitational field acting on an apparatus circling Earth

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- Elimination of Earth's atmosphere and hence of atmospheric disturbance in optical or other extra-terrestrial observations

All four are significant in experiments on gravitation now under development or in the planning stage.

Changes in gravitational potential find their most obvious application in tests of the strong equivalence principle. Pound and Rebka had measured the change in wavelength of a gamma ray transmitted 100 ft from the top to the bottom of the Jefferson Tower at Harvard. Zacharias[10] in 1959 suggested measuring the change in rate of a clock rising and falling a few hundred miles in a satellite in elliptic orbit. In 1974, Vessot and Levine[11] confirmed the redshift formula to 2 parts in 10^4 by measuring the changes in rate of a clock going 18,000 vertical miles in a suborbital rocket.

Microgravity is chiefly of use in experiments in which the effect under study influences a massive body. Three experiments are described here: 1) the orbiting gyroscope experiment proposed in 1959 independently by L.I. Schiff[12] and G.E. Pugh[13]; 2) an orbital test of the weak equivalence principle[14,14a]; and 3) an experiment to measure the Lense-Thirring drag on the plane of a satellite orbit by means of two counterorbiting satellites.[15]

All three of these experiments require acceleration levels well below the nominal 10^{-6} g that constitutes microgravity; in fact, the levels needed range from 10^{-10} g for the gyroscope experiment to a cross-track average below 2×10^{-13} g for the twin satellite experiment. Such accelerations are attainable by applying the principle of drag-free control, originated by Pugh[16] in 1959 and first successfully used in the Disturbance Compensation System (DISCOS) controller for the U.S. Navy's Triad transit navigation satellite, developed in the Stanford Department of Aeronautics and Astronautics under the leadership of D.B. DeBra.[17,17a] It is convenient to denote 10^{-12} g as 1 picogravity (pg). The measured in-track bias of DISCOS was 5 pg.

Another method for reaching low gravity proposed recently is the "flying drop tower,"[18] a large evacuated chamber constituting one of the space station free flyers, within which experimental packages can be allowed to float freely for up to 1 h. Nominally the flying drop tower yields accelerations at the nanogravity (ng) level, but as discussed below, the effective performance in gravitational physics experiments is closer to 1 pg.

The last two of the four benefits from space--cyclic change in the direction of gravity and elimination of atmos-

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pheric disturbance--are reviewed below in connection, respectively, with the equivalence principle and gyroscope experiments. Other applications are mentioned later.

The Gyroscope Experiment: Picogravity and Einstein

Two relativistic effects[12] make a gyroscope in orbit around a massive rotating sphere precess with respect to the framework of the fixed stars: 1) the geodetic precession, Ω_G, due to orbital motion of the gyroscope in the gravitational field of the central body; and 2) the motional or gravitomagnetic precession, Ω_M, due to the central body's rotation. In a 600-km polar orbit around Earth, the two effects are at right angles as shown in Fig. 1, Ω_G being equal to 6.9 arc-s/yr and Ω_M 0.44 arc-s/yr.

These precessions are extremely small and measuring them requires a gyroscope of unprecedented accuracy. In the experiment now under development at Stanford University with NASA support,[19] the goal is to measure each effect to 1 marc-s/yr or better, which means having a gyroscope with absolute drift-rate some seven orders of magnitude lower than those of the best inertial navigation instruments. Translated into the units customarily used for specifying gyroscope performance, the requirement is 10^{-11} deg/h.

A gyroscope may be an atomic nucleus, a macroscopic spinning body, a superconducting current, a sound wave

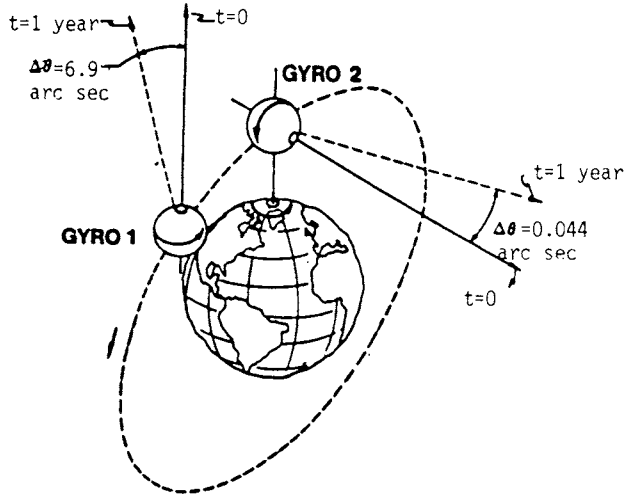

Fig. 1 Geodetic and motional precessions of a gyroscope in Earth orbit.

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propagating around a wineglass-shaped object, or a circulating laser beam. Laser and wineglass gyroscopes are orders of magnitude away from the desired performance. Nuclei and superconducting currents offer intriguing possibilities but are ruled out by their extreme susceptibility to magnetic disturbance. The only horse in the race is a supported spinning body, and no elaborate thought is needed to see that the most torque-free body is a precisely round, very homogeneous sphere.

Consider the simplest torque acting on a suspended sphere, the mass-unbalance torque, computed by assuming that the sphere is perfectly round and supported through its center of geometry but not quite homogeneous. If an acceleration f is applied transversely to the spin axis, the torque on the sphere will be $Mf\delta r$, where δr is the displacement between center of mass and center of support along the axis, and the drift rate will be

$$\Omega_u = 5/2 \cdot f/v_s \cdot \delta r/r \qquad (1)$$

where r is the radius of the ball and v_s its peripheral velocity. In the Stanford gyroscope, r is 19 mm and v_s is 2,000 cm/s. To establish gyroscope design, Eq. 1 is transposed into an inequality in terms of Ω_o, the maximum acceptable contribution to gyro drift from any one source and $\delta r/r$ is written in terms of variations in density of the sphere, with $\delta r/r < 3\delta\rho/8\rho$. Assuming approximately a limit of 0.1 marc-s/yr for the contribution to gyro drift, from this source

$$f\ (\delta\hat{\rho}/\rho) < \Omega_o\ v_s \approx 3 \times 10^{-17}\ \text{rad/s} \qquad (2)$$

Since the minimum variation in density that can reasonably be expected is a few parts in 10^7, the inequality (2) sets an upper limit of 100 pg on the average acceleration transverse to the gyro spin axis.

The gyroscope is illustrated in Fig. 2. A 1.5-in. (38-mm) diam fused quartz sphere, round to better than 0.8 μin. (20 nm), is coated with a thin layer of superconducting niobium and supported within an evacuated cavity by means of 20-kHz alternating voltages applied to three mutually perpendicular sets of electrodes.[20] On Earth, a potential difference of about 1 kV across the 1.5-mil (40-μm) gap between the rotor and housing is needed to support the rotor. In space, this can be reduced to 0.2 V. Because the suspension torques acting on the out-of-roundness of the rotor scale roughly as the square of the voltage, they, like the mass-unbalance torque, are greatly reduced by operating in space. With a rotor round to 0.8

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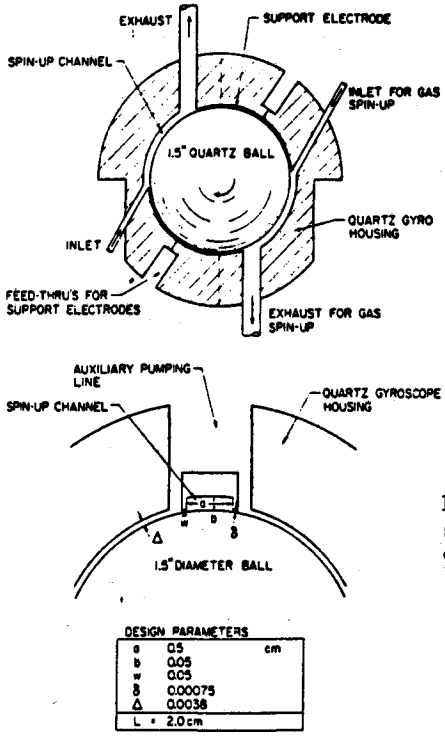

Fig. 2 Design of gyro housing showing support electrodes and differential pumping scheme for the gas spin-up system.

μin. and an average acceleration transverse to the spin axis below 100 pg, the gyro drift from this source also is below 0.1 marc-s/yr.

The gyroscope spins at 170 Hz, an optimum rate fixed by the balance of torques that are independent of spin speed against those that increase with speed owing to centrifugal distortion of the sphere. Spin-up is achieved by passing helium (He) gas at a pressure of about 20 Torr through circumferential channels around the rotor,[21] after which the housing is pumped down to its normal operating pressure of 10^{-10} Torr. A differential pumping scheme (Fig. 2) keeps the pressure in the electrode area during spin-up below 10^{-3} Torr, reducing drag forces and preventing electrical breakdown. The spin-up time is about 20 min; the characteristic spin-down time during gyro operations at 2 K and 10^{-10} Torr is 3,000 yr. A crucial issue of design is to eliminate residual torque from the spin system during normal gyro operations. Let Γ_s be the spin torque, which is of course parallel to the spin axis and ask how large its residual component Γ_r, perpendicular to the spin axis, may be. Let t_s be the spin-up time. Then, since $\Gamma_s = I\omega_s$ and $\Omega = \Gamma_r/I\omega_s$, the constraint on

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Γ_r is

$$(\Gamma_r/\Gamma_s) < \Omega_o\ t_s \tag{3}$$

or about 10^{-13}. The 11 orders-of-magnitude change in pressure between spin-up and final operation, combined with an averaging of T_r produced by rolling the spacecraft about a line parallel to the gyro spin axis, gives the necessary torque switching.

The gyroscope's direction of spin has to be read out to better than 1 marc-s. Figure 3 illustrates the principle of the gyro readout.[22] According to the London equations of superconductivity, a spinning superconductor develops a magnetic moment, the London moment, aligned with the instantaneous axis of spin, whose magnitude for a sphere of radius r rotating with angular velocity ω_s is

$$ML = 1/2(mc/e)r^3\ \omega_s\ G - cm^3 \tag{4}$$

where (mc/e) is the mass-to-charge ratio for the electron in electromagnetic units. For a 38-mm diam rotor spinning at 170 Hz, the London moment is 3.83×10^{-4} G - cm^3. To measure the direction of spin, the rotor is surrounded by a flat uniform loop of superconductor connected to a Superconducting Quantum Interference Device (SQUID) magnetometer. In general, three orthogonal loops are needed for a complete readout system, but in the rolling spacecraft a single loop with its plane parallel to the axis of roll suffices, provided other information is available (as it is) to determine the gyro scale factor and the roll phase angle. Measurements with a commercially available SQUID on a periodic signal at satellite roll rate have given a

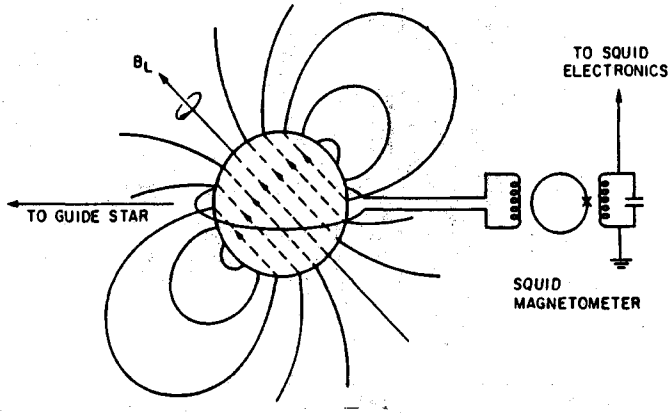

Fig. 3 London moment readout of superconducting gyroscope.

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resolution of 10^{-13} G in 140 hr, corresponding to an angular readout resolution of 0.7 marc-s.

The London moment readout has four vital merits: 1) it can be applied to measure the direction of spin of an ideally round and homogeneous rotor, 2) it has adequate angular resolution, 3) it is sensitive only in second order to the centering of the rotor in the readout loop, and 4) the reaction torque it exerts on the rotor is negligible.

Figure 4 illustrates the flight apparatus. Four gyroscopes and a reference telescope, formed into a single fused quartz assembly of 8-in. diam and a length of 2 ft 8 in., are mounted in a superfluid He Dewar and maintained at a common temperature of 1.8 K for the 2-year lifetime of the experiment. The gyroscopes are aligned with their spin axes parallel to the boresight of the telescope, two spinning clockwise and two counterclockwise. The spacecraft rolls about the line of sight to the guide star for a 10-min period, the roll phase being determined by means of separate roll-reference gyroscopes and a star blipper (a transversely mounted telescope that picks up a signal once each revolution from a bright star approximately 90° from Rigel or the celestial sphere). The gyroscope precessions are found by subtracting the gyro outputs from the output of the telescope (which has to be pointed within its ±60 marc-s range) and combining the difference signal with roll phase information. Because the satellite is in polar orbit and the orbit plan is chosen to coincide very nearly with the line of sight to the star, the star is in sight for

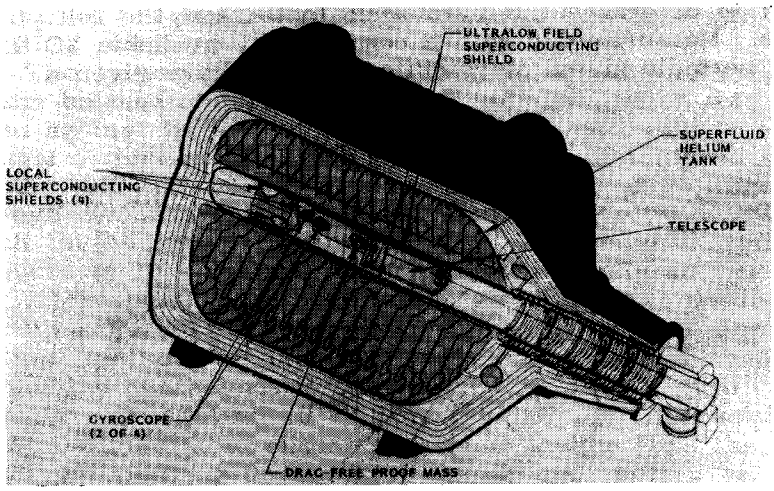

Fig. 4 Assembled gyro instrument: four gyroscopes, telescope, and drag-free proof mass operating at 1.8 K in a 2-year lifetime superfluid He Dewar.

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only about 60% of each orbit. Torque for pointing the spacecraft is obtained from the He boil-off gas from the Dewar, vented through proportional thrusters,[23-23b] with control signals taken from the telescope when the star is in sight and from the gyroscopes when it is occulted. The same thrusters referred to a drag-free proof mass also provide translational control of the spacecraft.

Submilliarc-second precision from the telescope also hinges on space operation for two reasons: microgravity and "seeing." Recall that to get below 1 marc-s/yr overall, individual error sources should contribute less than 0.1 marc-s apiece. On Earth, a telescope, cantilevered horizontally, of the size shown in Fig. 4 would sag under its own weight by about 0.2 arc-s, three orders of magnitude more than the budgeted amount. Although static sag might not matter, long-term drifts from creep would. In space, with a rolling spacecraft, the effects of sag and creep are utterly negligible. Seeing limitations due to atmospheric turbulence, which on Earth is typically 0.1 to 3 arc-s (and thus again three to four orders of magnitude beyond budget) are likewise eliminated in space. One potentially serious source of error not removed by space is thermal distortion, but in our apparatus that is eliminated by working at cryogenic temperatures, where temperature control is easy and coefficients of expansion vanishingly small.

The line of sight to the star is not an absolute direction in space. It shifts about for four reasons: 1) aberration, 2) parallax, 3) relativistic deflection of starlight by the sun, and 4) proper motion. Proper motion is a nuisance, causing errors that must be eliminated; the other three are intriguing effects that enrich the experiment.

The current uncertainty in proper motion of the chosen guide star, Rigel, is believed to be 0.9 marc-s/yr in declination and 1.7 marc-s/yr in right ascension.[24] Surprisingly, these turn out to be the dominant errors in the experiment, affecting, respectively, the measurements of Ω_G and Ω_M. Ultimately, proper motion should be no concern because, as data improve, the results can be retroactively corrected. The present best hope for improvement is through data from the European astrometric satellite HIPPARCOS, scheduled for launch in 1988. Other more specialized techniques also may be tried.

Aberration, being determined by the ratio v/c, where v is the velocity of the telescope across the line of sight and c is the velocity of light, provides signals of known amplitude at annual and orbital period, helpful (indeed essential) in calibrating the scale factor of the experiment.[25] Over the course of a year, the relativistic deflec-

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tion of starlight by the sun traces the curve shown in Fig. 5,[26] which, having a signature different from those of gyroscope precessions, proper motion, or aberration, can be separated from them in data reduction. Thus, the experiment gives a new measure of light deflection, good to about 1% and thus comparable with the VLBI result.

Rigel is about 100 parsec from the solar system, a distance known from Earth-based parallax measurements to about 25%. The parallax appears as a phase shift on the annual aberration; in the gyroscope experiment it can be determined to about 1%.[27] Thus a byproduct of the experiment is a much improved measurement of the distance to Rigel.

The requirement on translational control of the spacecraft, already noted, is 100 pg. More will be said on the meaning of this figure in a later section.

The Equivalence Principle Experiment: Picogravity and Galileo

The word "principle," as used by physicists, means a dogma that is believed but not understood. Mach's principle, relating local inertia to the large-scale structure of the universe, is one such principle; one other is the equivalence of gravitational and inertial mass, first tested by Galileo, first recognized for what it was by Newton, and first elevated to the status of a principle by Einstein.

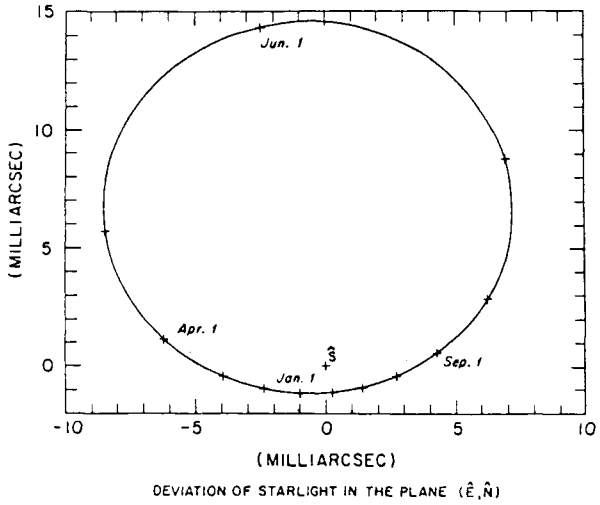

Fig. 5 Signature of realitivistic deflection of starlight by the sun as observed in the gyroscope experiment.

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The experimental fact is the universality of free fall: all bodies, whatever their composition, fall in vacuo with the same acceleration. Universal free fall has now been verified with great precision, the most trustworthy measurements being those of Roll, Krotkov, and Dicke, who found agreement for gold and aluminum test masses to within 3 parts in 10^{11}. Consider the significance of the observation in a Newtonian context. Newton proposed two formulas: the law of motion, $F = ma$, and the law of gravitation, $F = GMm/r^2$. The mass, m, has two distinct meanings in the two formulas, one as the receptacle of inertia, the other as the source and receptacle of gravitation; yet somehow the two are identical. Stated another way, if m_i and m_g are respectively inertial and gravitational mass, then for any two bodies A and B, regardless of what substance they are, the quantity

$$\eta = 2\,[(m_i/m_g)_A - (m_i/m_g)_B]/[(m_i/m_g)_A + (m_i/m_g)_B] \qquad (5)$$

appears to be identically zero. It was just this identity that Einstein denominated a principle (weak equivalence) and extended (strong equivalence) to all the laws of physics in accelerated frames, whether the acceleration is inertial or gravitational in origin. Strong equivalence is the basis on which it becomes possible in general relativity to represent gravitation by a curvature of spacetime. Contrary to what is sometimes thought, however, general relativity does not explain equivalence. The principle is an assumption that, once made, allows the effects of gravity to be represented thus. The phenomenon remains a mystery and still needs testing.

Despite the amazing precision of Roll, Krotkov, and Dicke's result, questions remain. The stability of the proton, for example, may, as Yang and Lee saw many years ago,[28] be attributable to a new long-range force coupled to atomic number. This hypothesis, if true, would at some level violate equivalence.

Three approaches to testing equivalence have been tried over the centuries. Galileo dropped bodies of different materials from the Leaning Tower of Pisa[29]; Newton compared the periods of two pendulums of equal length with different bobs[30]; and Eötvös looked for disturbances on a torsion balance with different masses at the two ends.[31] Of the three methods, Eötvös' has proved the best. It requires the masses to be subjected simultaneously to opposed centrifugal and gravitational accelerations. For centrifugal acceleration, Eötvös used the rotation of Earth, which produces at latitude lambda a component parallel to Earth's surface of magnitude 1.4 sin 2λ

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cm/s^2. This deflects the torsion fiber from the vertical until balanced by an equal and opposite component of Earth's gravitational attraction. Suppose the arm joining the two masses is initially aligned east to west. If equivalence holds, the two components of acceleration on each mass will exactly balance; if it does not hold, there will be a torque, and the arm will turn through a small angle θ proportional to the ratio η divided by the torsional constant of the fiber. Now let the torsion head be turned through 180°. The arm also will turn, but with the two masses interchanged, the deflection will be in the opposite direction and the total rotation will be (180° - 2θ).

Eötvös and his colleagues succeeded in checking equivalence to a few parts in 10^8 but were limited by difficulties with elastic hysteresis in the torsion fiber. Accordingly Dicke,[2] when he revived the experiment in the 1950s, chose a different method based on comparing effects from the gravitational attraction of the sun balanced against the acceleration from Earth's orbital motion about the sun. Earth's rotation made the torsion arm turn continuously with respect to the Earth-sun line; the experiment consisted of looking for a 24-hr variation in the orientation of the balance with respect to a line fixed on Earth. The driving acceleration was less than that in Eötvös' experiment (0.6 cm/s^2 instead of 1.3 cm/s^2), and the daily changes in temperature, atmospheric pressure, and the locations of human beings with respect to the apparatus introduced disturbances with a 24-hr period. However, the problem of elastic hysteresis was expunged. After 7 years of brilliant, arduous work, Dicke and his colleagues set the 3 parts in 10^{11} limit on equivalence.

Space offers the chance of an improved test of equivalence for two reasons. First, an experiment can be devised that compares effects from the gravitational attraction of Earth and the centrifugal acceleration from orbital motion around it, and these, being 820 cm/s^2 in a 650-km orbit, are three orders of magnitude larger than the accelerations used by Eötvös and Dicke. Second, whereas Earth-based experiments are limited in practice by seismic noise, in space there is the opportunity in the right circumstances for a quieter environment. Ultimately, an orbital experiment determining η to 1 part in 10^{17} or 10^{18} seems possible--six to seven orders of magnitude beyond the Roll-Krotkov-Dicke limit.

Far and away the best method of testing equivalence on Earth has been with the torsion balance. Roll, Krotkov, and Dicke's experiment reached a precision five orders of magnitude higher than the best pendulum experiment.[32] Given this, one might expect the right approach for space

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to be to orbit a torsion balance around Earth. Not so. In space, a new factor comes into play: gravity gradient disturbance. A broad study of the options finally leads the experiment concept full circle back to Galileo and freely falling bodies.

Figure 6 illustrates the scheme for an orbital equivalence principle experiment devised some years ago by P.W. Worden, Jr. and the author.[14,33] Different suggestions were made earlier by Pugh[34] and by Chapman and Hanson.[35] In the orbital equivalence principle experiment, two bodies, a rod and a cylinder of different materials, are floated concentrically in an evacuated space within a drag-free satellite (not shown in Fig. 6), with the inner body serving as the drag-free proof mass. The masses are constrained from lateral motion but are free to move along their common axis. The satellite follows a circular orbit, preferably polar, and is held oriented in a fixed direction in inertial space, with the common axis of the two masses lying in the orbit plane. Any violation of equivalence will cause a periodic differential acceleration between the two masses at orbital frequency. Instead of falling 179 ft from the Leaning Tower, they have been dropped on a repeating cycle all the way around Earth. The experiment needs a method of restraining the masses laterally, a method of keeping them centered longitudinally, and a method of reading out the differential acceleration.

As with the gyroscope experiment, cryogenic techniques are a great aid. Low-temperature operation reduces disturbances on the masses from radiation pressure and certain effects of residual gas in the cavity. It also allows use of superconducting techniques in the suspension, magnetic shielding, and position readout of the masses. Figure 7 illustrates a test mass assembly, adapted to a ground-

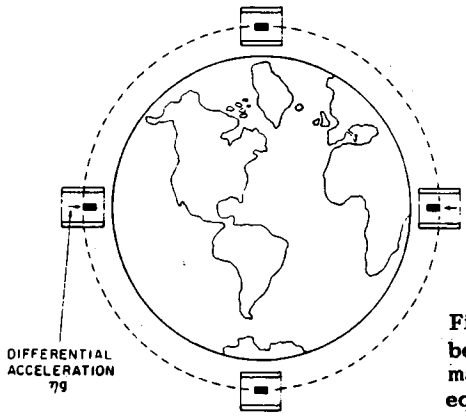

Fig. 6 Differential acceleration between two concentric test masses in Earth orbit if equivalence principle is violated.

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based experiment but very similar to what would be flown in space. The masses, which are either superconductors or coated with superconductor, are supported in two independent bearings, each in the form of a cradle or sheath made up of superconducting niobium wires stretched tightly parallel to the cylinder axis, with currents flowing in opposite directions in adjacent wires to provide very stiff lateral support but negligible restraint for motions along the cylinder axis.

Figure 8 illustrates the principle of the circuit used for measuring motions of one or other of the two masses with respect to the spacecraft (or laboratory apparatus in

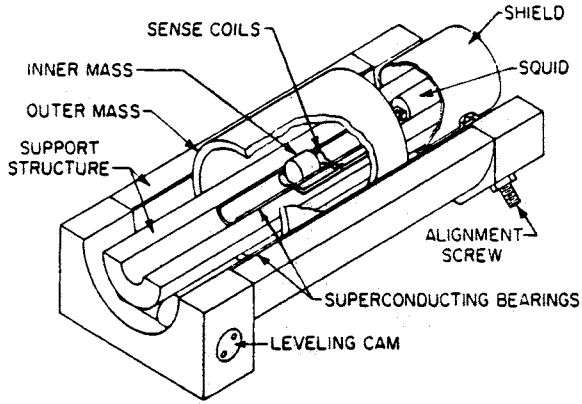

Fig. 7 Proof-mass test assembly for ground-based version of equivalence principle experiment.

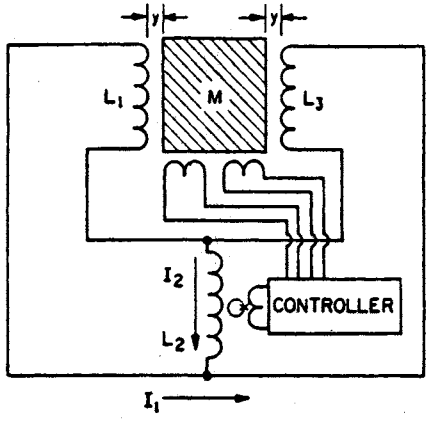

Fig. 8 Principle of position detector for measuring displacement of proof mass with respect to the satellite.

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a ground-based experiment). Facing opposite ends of the mass are two equal inductances, L_o,L_o . As long as the mass stays centered, no current will flow in L_2, but if it is displaced through a distance $+\Delta x$, L_o will increase and L_o' decrease, making a current I_2 proportional to ($I\ \Delta x$) flow in L_2, where it can be detected by the SQUID. The SQUID output controls a servo to keep the mass centered. In a ground-based experiment, centering is done by the tilt coils shown in Fig. 8. In space, the centering forces are applied at the ends of the mass.

The experiment compares the control accelerations needed to keep the two masses centered. For proper comparison, both the control gains and the free periods of the masses parallel to their common axis must be simultaneously matched. An ingenious superconducting circuit devised by P.W. Worden, Jr.,[33] partly on the basis of a suggestion by H.J. Paik, provides the necessary matching functions and subtracts the two control currents to give an output directly proportional to any differential acceleration between the masses.

Why abandon the torsion balance? Gravity gradients are the decisive factor. They affect the experiment in two ways: the disturbance from Earth and disturbances from motions of the satellite. Consider a torsion balance in which the test object is made up of two masses (m/2 each) in the form of semicircular rings of diameter D. Let the ring as a whole have a residual quadrupole mass moment (J_2I), where J_2 is the quadrupole coefficient and I is the moment of inertia on D^2. Let the central body (the sun or Earth), from which is taken the driving acceleration to test equivalence, have mass M and be at a distance R. Denote the torque on the balance from a mismatch η in equivalence by Γ_E and the gravity gradient torque by Γ_{gg}. Then very nearly

$$(\Gamma_{gg}/\Gamma_E) \sim (J_2\ D/\eta\ R) \qquad (6)$$

Exchanging the sun for Earth as source reduces R by a factor of 2×10^4. Along with the three orders-of-magnitude improvement in driving acceleration comes an increase in the disturbance acceleration by seven orders of magnitude in absolute value and four orders of magnitude in relative value. And the more precisely one is trying to measure η, the more significant is the disturbance. In a measurement of η to 1 part in 10^{11} on Earth, gravity gradient torques are of little importance. In an orbital experiment at 1 part in 10^{17}, they are overwhelming. The same is true for gravity gradient noise from motions of the spacecraft.

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In the free-fall experiment, gravity gradient disturbances are also a major issue, but something can be done about them. The requirement is that the centers of mass of the two test bodies should coincide. Assume (an oversimplification) that the only error comes from a displacement δr between the two masses along their common axis. In circular orbit, this results in a constant acceleration, which may be ignored, and a periodic differential acceleration δf_{gg} at twice orbital rate and of amplitude $3GM\,\delta r/2R^3$ or $2 \times 10^{-9}\ \delta r$ g. To keep δf_{gg} below the amplitude of the acceleration from a violation of equivalence at the 10^{17} level, the average distance between the two mass centers should not exceed 1 Å.

At first glance, such precision of centering would seem beyond reach. Even with the most careful choice of materials, inhomogeneities will make for a displacement of 100 Å or more between the mass center of a test body and its geometrical center. Brownian motion will cause random fluctuations in the positions of each test mass of rms amplitude 0.1 T Å, where T is the natural period along the free axis. In reality two factors, or rather two aspects of a single factor, combine to make the centering issue tractable.

First, whereas the gravity gradient disturbance δf_{gg} is doubly periodic in the orbit, the Eötvös signal we are trying to measure is singly periodic. Because the doubly periodic term can be removed from the output in data reduction, the true limit is set by something else, namely the existence in an elliptic orbit of a singly periodic subharmonic of δf_{gg}. The amplitude of the subharmonic is of order $\epsilon\ \delta f_{gg}$, where ϵ is the eccentricity; hence, with an ϵ of 10^{-3} the centering requirement may be relaxed to 1000 Å. Second, the doubly periodic term in the output provides a reference signal that may be used in a slow servo loop for adjusting the mean position of one test mass and forcing the two mass centers to coincide.

A like requirement of 1000 Å on mass centering comes from gravity gradient disturbances due to motions of the spacecraft. In addition, gradients from Earth and the spacecraft impose limits on the shape and size of the test masses. In a field gradient, center of mass and center of gravity only coincide for isoinertial bodies and then only approximately so, unless the body is a homogeneous sphere.[36] For a tube of length 2ℓ, mean radius a, and wall thickness 2t, the requirement is $\ell^2 = (3/2)(a^2 + t^2)$; that is, the ratio of length to diameter should be a little greater than 6:5. Second-order terms set a limit on size for the outer body.

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The demands on drag-free control for the equivalence principle experiment are even more stringent than for the gyroscope experiment. They arise partly from the need to guard the test masses from disturbance and partly from measurement considerations. To determine η to 1 part in 10^{17} with a driving acceleration of 1 g, the differential acceleration has to be measured to 10^{-17} g. If the subtraction circuit is good to 1 part in 10^5 or 10^6, the drag-free performance needs to be 1-10 pg. The constraint from disturbances lies in the same range.

The Twin Satellite Experiment

A satellite in orbit around a massive body such as Earth may be regarded as a gyroscope. In 1918, many years before Schiff and Pugh had thought of the orbiting gyroscope experiment, W. Lense and H. Thirring[37] calculated the effect of relativistic frame dragging on a satellite in orbit around a rotating central body. The rate of advance of the right ascension of the ascending node is

$$\dot{\vec{\Omega}}_{LT} \; (2 \; G \; \vec{J}/c^2 a^3 (1 - e^2)^{3/2}) \qquad (7)$$

where $\vec{J}$ is the angular momentum of the central body and a and e are the semimajor axis and eccentricity of the orbit. (There is a regrettable but almost unavoidable clash of notation between the use of Ω to represent precession rate for a gyroscope and its use to represent nodal angle for a satellite orbit. Hence, geodetic precession is represented by $\vec{\Omega}_G$ above and by $\dot{\vec{\Omega}}_G$ in this section.) Note that $\dot{\vec{\Omega}}_{LT}$ is independent of the orbit inclination, though it becomes pathological in an equatorial orbit. The value for a 650-km orbit around Earth is 0.18 arc-s/yr, exactly four times the Schiff precession for an orbiting gyroscope in a polar orbit of the same altitude. In addition to $\dot{\Omega}_{LT}$ there are effects, independent of orbit altitude, from the solar geodetic precession, which causes a nodal advance $\dot{\Omega}_G$ of 17.2 marc-s/yr and a rotation di/dt in inclination angle of 6.8 marc-s/yr.

Some years ago it occurred to R.A. Van Patten[38] that with a drag-free satellite in polar orbit, the orbit plane might be stable enough to allow a measurement of ($\dot{\Omega}_{LT} + \dot{\Omega}_G$). Disregard gravitational perturbations for the moment and consider the limit on nongravitational disturbances such as air drag, solar radiation pressure, and interactions with Earth's magnetic field. For a satellite experiencing a cross-track acceleration f, the instantaneous rotation of the

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orbit line is $\Omega = f/v$, where v is the orbital velocity. So to reach a precision $\dot{\Omega}_o$ in determining $\dot{\Omega}_{LT}$, the upper limit on f averaged around the orbit is

$$\bar{f} < \dot{\Omega}_o \, V \tag{8}$$

Since $\dot{\Omega}_{LT}$ drops off as a^3 and v as $a^{1/2}$, the limit $\bar{f}$ scales with the semimajor axis of the orbit as $a^{-7/2}$. To make $\dot{\Omega}_o$ less than 1% of $\dot{\Omega}_{LT}$ in a 650-km orbit, the average cross-track acceleration must be less than 0.2 pg. In the 12,238-km-radius orbit of the Laser Geophysical Satellite (LAGEOS), the limit would be 0.018 pg.

With a drag-free satellite controlled like DISCOS to 5 pg, one may reasonably expect the cross-track acceleration on orbit to average less than 0.2 pg. What of gravitational perturbations? They are from two sources, the figure of Earth and lunisolar effects, with the latter including both direct actions of the sun and moon on the satellite orbit and indirect effects from Earth tides and ocean tides. The direct problem lies in calculating the nonrelativistic regression $\dot{\vec{\Omega}}_Q$ due to Earth's quadrupole mass moment, J_2, which has magnitude $3/2 \; \bar{\omega}_o \; J_2 \; [R_e/a(1 - e^2]^2 \cos i$, where R_e is the mean radius of Earth, and i and ω_o are the inclination and mean motion of the orbit. The quantity R_e is well known, and $\bar{\omega}_o$, a, and e can be determined with great precision for any given satellite from tracking data, but appreciable uncertainties exist in J_2 and cos i. To determine the error $\Delta\Omega_Q$ after time t, one first differences with respect to J_2 and i, and then integrates with respect to time to allow for the variations in i that arise from geophysical and lunisolar perturbations. Substituting coinclination $i' = (\pi/2 - i)$,

$$\Delta\Omega_Q = K \; J_2 \int_o^t \left[\left(\frac{\Delta J_2}{J_2} \right) \sin i' + \cos i' \; \Delta i' \right] dt \tag{9}$$

where K condenses $3 \; \omega_o [R_e/a(1 - e^2)]/2$. Currently, J_2 is known to a few parts in 10^6. The uncertainty in $\Delta i'$ depends on 1) uncertainty in position of Earth's pole with respect to inertial space and 2) uncertainties in tracking the satellite. From LAGEOS data, the uncertainty in the pole appears to be a few milliarc-second. Tracking uncertainty depends on technique. For a laser-tracked satellite, the long-term average appears to be a few milliarc-second; for one with conventional Döppler radar tracking it is nearer 30 marc-s. Detailed investigation shows that the uncertainty in $\Delta\Omega_Q$ from ΔJ_2 can be made manageable by

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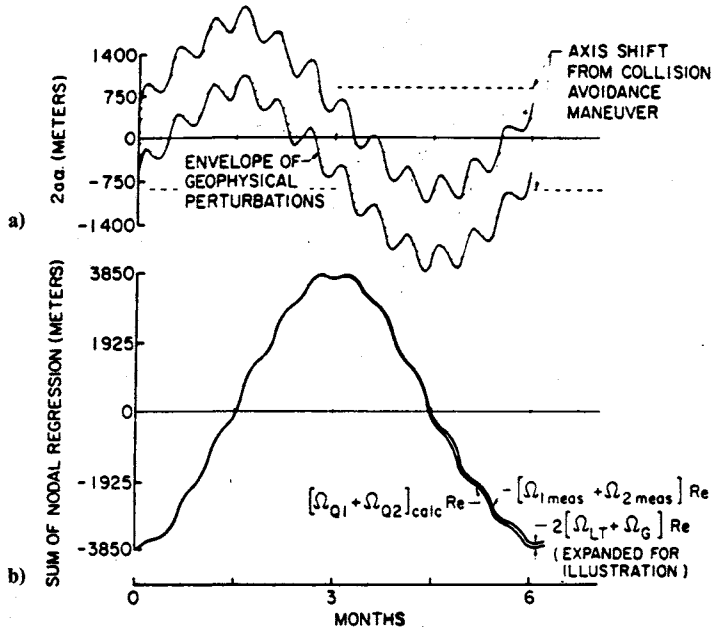

Fig. 9 Extraction of relativity data from twin satellite measurements: a) variations over time of lateral distance between satellites as they pass over the poles; b) relativity data obtained from difference between observed nodal precession and the classical precession calculated from polar measurements.

selecting the proper orbit node and by trimming the orbit initially to within 100 arc-s of the pole, but that the uncertainty Δi causes errors of about $6\Omega_{LT}$ for a Döppler-tracked satellite and about $0.4\Omega_{LT}$ for a laser-tracked satellite.

A solution, proposed by Van Patten and the author,[15] was to make use of two counter-orbiting drag-free satellites in polar orbits, initially adjusted by in-flight corrections to be very nearly equal and opposite. The satellites would be timed to pass each other nearly over the north and south poles but planned in such a way that collisions are avoided. At each polar passing, the slant range distance between the two spacecraft would be measured by satellite-to-satellite Döppler ranging, good to about 1 cm; whereas at lower latitudes, conventional ground-based Döppler tracking would be applied to determine the nodal regression rates with respect to Earth--data that could be combined with universal time (UTI) data to give nodal regressions with respect to inertial space.

The satellite-to-satellite ranging data fixes the angle 2α, the sum of the coinclinations $(i_1 + i_2)$ of the two

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orbits. The instantaneous sum of the regression rates and $\dot{\Omega}_{Q_1}$ and $\dot{\Omega}_{Q_2}$ arising from the geophysical perturbations is given by

$$[\Omega_{Q_1} + \Omega_{Q_2}]_{calc} = 2K\, J_2\, \alpha \qquad (10)$$

independent of the uncertainty in position of either satellite with respect to the poles. The lunisolar perturbations similarly have equal and opposite effects on the two satellites; on the other hand, the relativity effects ($\Omega_{LT} + \Omega_G$) make both satellites precess in the same direction. Writing $\Omega_{i\ meas}$ and $\Omega_{2\ meas}$ for the observed nodal advances of the two satellites (as tracked from ground stations), we get for the sum of the two relativistic precessions after time t

$$2(\Omega_{LT} + \Omega_G) = \Omega_{1\ meas} + \Omega_{2\ meas} - 2K\, J_2 \int \alpha\, dt \qquad (11)$$

The form of data to be expected is shown in Fig. 9a) and b), with a) being the structure of lunisolar and geophysical perturbations in the satellite-to-satellite ranging information and b) the sum of the nodal motions. To avert catharsis in the shape of a head-on collision between the two spacecraft, a slight correction has to be made to one or other of the orbits every few months. This can be done easily without loss of relativity data.

A detailed error analysis suggests that in 2-1/2 years, the errors from geophysical perturbations can probably be reduced to 1%. The chief difficulty, apart from the elaborate data reduction process, is the uncertainty in UTI, which may put a limit of about 5% on the ultimate precision of the experiment.

Recently, I. Ciufolini[39] has suggested a variant on the twin satellite experiment related to the LAGEOS program. LAGEOS has an orbit of radius 12,220 km and an inclination of 109.1°. Currently, NASA and the Italian space organization are developing LAGEOS II, scheduled for launch in 1989 into an orbit of similar radius but with a 55° inclination. At LAGEOS' altitude, Ω_{LT} is reduced by a factor of 5 to 37.2 marc-s/yr, whereas Ω_G remains the same. Cuifolini's idea is to change the inclination of LAGEOS II to 70.9° so that the ascending nodes of the two satellites move at approximately equal rates in opposite directions. The Newtonian regression rates $\pm\Omega_Q$ are $\pm$0.34°/day, or 4.5 x 10^8 marc-s/yr. To extract relativity data to 10%, the two signals have to be differenced to 1 part in 10^8.

The motivation for using two satellites in Ciufolini's proposal is slightly different from that in the proposal by

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Van Patten and the author. As Eq. (9) shows, there are in general two sources of error in $\Delta\Omega_Q$, the uncertainty ΔJ_2 in knowledge of Earth's quadrupole moment and the uncertainty $\Delta i'$ in measuring the orbit inclination. The idea here was to make the effect of ΔJ_2 negligible by placing the satellites in near-polar orbits and to use counterorbiting to get rid of Δi. In orbits with coinclinations of ± 19 deg, two things are different. First, in differencing two signals to 1 part in 10^8, one can no longer neglect the uncertainty of a few parts in 10^6 in J_2. Second, the uncertainties $\Delta i_1'$ and $\Delta i_2'$ can no longer be subtracted, because with large regression rates there will be periods when the ascending nodes of the two orbits are at right angles and $\Delta i_1'$ and $\Delta i_2'$ are uncorrelated. The plan must be to use counterorbiting to get rid of the J_2 error and take what one must in inclination error. The hope is that with laser tracking the uncertainty in $\Delta i'$ is less than with conventional Döppler tracking. LAGEOS has one advantage from its large orbit radius, namely that the relative significance of the higher order geophysical perturbations is reduced because they scale as $a^{-(n3/2)}$, where n is the order of the harmonic.

The discussion hinges on technical issues in the reduction of LAGEOS data. Currently, the claimed rms uncertainty in measurement of the pole from LAGEOS I data over a 7-year span is ± 2 marc-s,[40] which, if true, would contribute an error of $\pm 35\%$ to the overall uncertainty in Ω_{LT}. Other rather drastic uncertainties manifest themselves in the disagreement between the long-term measurements of UTI from LAGEOS and VLBI data.[41] With LAGEOS, altitude air drag is of little significance. However, because solar radiation pressure puts an acceleration of 5×10^{-10}g on LAGEOS, the cross-track averaging must be good to 1 part in 3,000 to reduce the error it contributes to 10% of Ω_{LT}--without benefit of drag-free control.

In summary, the twin satellite experiment, in whichever form, places an even stricter requirement on drag performance than either the gyroscope or equivalence principle experiments.

Considerations About Drag-Free Performance and a Flying Drop Tower

The three experiments just described, and others to be mentioned later, all require accelerations constrained to the picogravity range. This constraint might seem to preclude use of the shuttle or space station in gravitational physics. Actually it does not. Several schemes exist for operating experiments in a quasi-drag-free mode.

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One is to enclose the experiment package in a cage with a clearance of about 1 ft and use it as a drag-free reference body for the surrounding vehicle. The other is the "flying drop tower."

The idea of the drop tower, as presently conceived,[18] is to convert one of the shuttle main tanks into a space station free flyer. The interior dimensions of the tank are 97 ft in length and 27.6 ft in diameter. Evacuated and oriented with its long axis tangential to the orbit, it can provide a shielded region within which experimental packages can be "dropped." Air drag depends on orbit altitude but may be as low as 0.1 microgravity (μg), whereas the self-gravitational attraction of the tank on packages within it is of order 1 ng. Orbital dynamics calculations, taking both drag and self-gravitation into account, show that a package started at the forward end of the tank traces a path aftwards combining the parabola of fall and an ellipse of 10.6 ft by 5.3 ft, with major axis tangent to the orbit. The time of fall is about 1 h.

At 1 ng, the self-gravitation of the drop tower still seems too large for gravitational-experiment purposes. In reality the vista is not so bleak; before discussing why, one needs to examine the limitations on ordinary drag-free systems, illustrated by example from the gyroscope and equivalence principle experiments. These limitations are of three kinds: 1) limitations on long-term average drag, 2) noise accelerations, and 3) accelerations on an object within the spacecraft whose mass center does not coincide with the drag-free proof mass.

The practical limit on long-term average drag is set by self-gravitation from the spacecraft, as B.O. Lange proved many years ago.[42,43] With DISCOS, the level was 5 pg, and drastic measures were needed to get that low. The power and telemetry modules for the spacecraft were mounted on extensible arms so that on orbit they could be put far from the proof mass. The control gas was stored in a pair of toroidal tanks arranged like Helmholtz coils symmetrically on opposite sides of the proof mass and kept at equal pressure to eliminate bias from the gravitational attraction of the gas. Much trouble developed from the design requirements of the position detector for the proof mass. The readout was based on capacitance measurements between the proof mass and three mutually perpendicular pairs of electrodes in a ceramic housing. The housing attracted the mass and so had to be made symmetrical and of very homogeneous material. Other features of the design made for a rather large gap (7 mm) and hence for capacitances that were small (0.6 picofarads [pF]) and hard to measure, requiring the presence of circuit elements

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close in. These in turn were a source of gravitational bias. Not only did the attraction of each element (and other nearby bodies) on the proof mass have to be computed individually, but it was necessary also to take into account their quadrupole mass moments, and in one instance the next higher mass moment.[44] The overall bias was compensated out by installing a carefully shaped compensating mass.

Only two methods appear to be available for improving on the 5-pg drag-free performance of DISCOS. One is to adopt a different kind of position readout--optical, for example--that would allow for an increase in distance between the proof mass and the space in which it is contained. The other is to spin the spacecraft so that the bias from self-gravitation is averaged out--in one plane at least. Both approaches have been studied. In the gyroscope experiment the spacecraft does roll about the line of sight; more is said below about the effectiveness of the cross-roll averaging of the biases. A two-axis ground-based simulator of a drag-free controller with large cavity and optical pickoff has been built and tested at Stanford[45]; but systems of this kind have yet to be flown. The flying drop tower, if it were converted to a drag-free system, would preeminently have a large cavity; however, a concerted design effort would be needed to establish a region of low acceleration near the center of mass of the tank.

Only one point in any drag-free satellite is even nominally free of acceleration: the center of the proof mass. In a nonrolling spacecraft, all other points are subject to accelerations from Earth's gravity gradient, whereas in a rolling spacecraft, any point not exactly on the roll axis experiences a centrifugal acceleration.

Consider gravity gradient effects first. Resolve the total displacement $\vec{\ell}$ of point P from the proof mass O into two components $\vec{\ell}_\rho$ and $\vec{\ell}_n$, respectively, in and at right angles to the orbit plane. For simplicity, assume a circular orbit of radius R. The normal displacement $\vec{\ell}_n$ will result in a constant acceleration $g\ell_n/R$ towards the orbit plane; so, for example, if ℓ_n is 20 cm and R is 7×10^8 cm (630-km altitude), the acceleration is 30 ng. The parallel displacement $\vec{\ell}_p$ will produce an acceleration $\vec{f}_p$ having two components: a steady term f_{ps} along $\vec{\ell}_p$ of magnitude $g\ell_p/2R$ plus a cyclic term f_{pc} of fixed magnitude $3\ g\ \ell_p/2R$ rotating at twice orbital frequency in a plane parallel to the orbit plane. With an ℓ_p of 20 cm and an orbit radius of 7×10^9 cm, the terms f_{ps} and f_{pc} have magnitudes 15 ng and 45 ng. The accelerations f_{ps}, f_n and f_{pc} in the examples just given are, respectively, 3,000, 6,000, and 9,000 times the DISCOS limit of 5 pg.

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Consider next the situation in the gyroscope experiment with its nominal drag-free requirement of 100 pg. The four gyroscopes are in line ahead on the boresight of the telescope at distances 20-45 cm from the proof mass. The orbit plane is chosen to be close to the line of sight, so ℓ_n is small (though not quite negligible--for the gyroscope at 45 cm in an orbit regressing 2°/yr from initially perfect alignment, the value of ℓ_n at the end of the year is 1.5 cm), but ℓ_p is very large. What is the point of drag-free control at 100 pg, when the gyroscopes experience constant accelerations 140 to 315 times that limit and cyclic accelerations three times as large again? The answer lies in the configuration of the gyroscopes. Their spin axes, being aligned with the boresight, are almost exactly parallel to $\overline{\ell}_p$. As a result, the constant acceleration f_{ps}, though it may affect the preload voltage for the gyro suspension system, does not directly cause any appreciable gyro-drift torque. It is the cross-axis acceleration that needs to be eliminated, and that is the purpose of the drag-free controller. As for f_{pc}, the cyclic acceleration, it does have a cross-axis component, but because that is sinusoidal, its effects in the orbit under consideration average nearly to zero.

Similar considerations apply to the centrifugal acceleration due to spacecraft roll. Such accelerations are surprisingly large; in a spacecraft with a 10-min roll period, as in the gyroscope experiment, the acceleration on a point y mm from the roll axis is 11 y ng. To reduce it to 0.1 ng, the gyroscopes would have to be within 100 μm (0.25 mil) of the roll axis. Fortunately, the effects average to a level roughly determined by the uniformity of the roll rate (e.g., 1 part in 10^4, or to about y pg).

The spacecraft roll also helps improve the cross-axis performance of the drag-free controller nominally to the 10^{-4} uniformity of the roll rate. However, in reality performance probably is not improved this much because of effects such as the tidal attraction of Earth on the liquid He in the Dewar, which tend to make the mass distribution lopsided with respect to inertial space.

The third limiting factor on drag-free performance is acceleration noise. Examples are noise from the position detector for a drag-free proof mass and, in the gyroscope experiment, pointing noise in the telescope. The accelerations arising from pointing noise are startlingly large. Again, they occur because the gyroscopes are not at the center of mass of the spacecraft. Let the distance from the center of mass (assumed to be nearly coincident with the drag-free proof mass) again be ℓ_p, let the bandwidth of the pointing servo be ω, and let the rms pointing error

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be $\hat{\theta}_p$. Then the acceleration $\hat{fv}$ will be $\omega^2 \ell_p \hat{\theta}_p$, and with $\omega_p \approx 25$ rad/s, $\ell_p \approx 45$ cm and $\theta_p \approx 10$ m arc-s, $\hat{fv}$ is 1.4 μg. When the star is occulted and reference is provided by the gyroscopes, f_v is even larger. Fortunately, this noise acceleration has no effect on gyro drift. A good part of it, being above the bandwidth of the gyro suspension system (4 rad/s), is not even felt by the gyro rotor; the rest of the noise acceleration averages. The one point to watch is that noise acceleration should not be allowed accidentally to switch the gyro suspension to a higher preload level.

Having seen the nonobvious accelerations that occur with conventional drag-free systems, it is instructive to return to the flying drop tower with its obvious 1 ng self-gravitation. Consider the effect on a free-floating equivalence principle experiment. At first blush, the experiment would seem to be hopelessly degraded by the presence of an acceleration two to three orders of magnitude larger than the 1-10 pg limit established above, but that is not the case. For the requirement is on the differential acceleration between each test mass and the experiment container. Now the gravitational attraction of the drop tower acts on both the test mass and the experiment container. Provided the centers of mass coincide and there are no appreciable complications from higher order mass moments of the experiment container, the two accelerations will be equal. The equivalence principle experiment is saved by the equivalence principle.

A similar consideration applies to suspension torques on a gyroscope mounted in an apparatus inside the flying drop tower. If the test object (gyro or proof mass) is displaced a distance $\vec{\ell}$ from the center of mass of the spacecraft, there are, as seen above, differential accelerations from Earth's gravity gradient, but they are governed by the same kinds of considerations in the flying drop tower as in a regular drag-free system.

The flying drop tower is a promising concept for gravitational physics experiments. Its chief shortcomings are optical access to the outside world and the relatively short drop time (1 h). Techniques to overcome the latter are not hard to find.

Other Experiments on Gravitation in Space

Four other proposals for experiments in space designed to investigate gravitational physics phenomena are now briefly mentioned.

The first, Precision Optical Interferometry in Space (POINTS), is a proposal by R.M. Reasenberg and

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I.I. Shapiro[46,46a] for a large orbiting Michelson stellar interferometer, with microarc-second resolution, which is intended among other things to yield a measurement of the deflection of starlight by the sun with sufficient accuracy to detect the second-order term in the deflection. Space is essential to eliminate seeing limitations. POINTS has many applications; the principal challenge in the design lies in getting microarc-second stability in the presence of thermal distortion and gravity gradient disturbances.

The next three proposals all require drag-free technology. One is Starprobe, a solar science spacecraft conceived some years ago,[47] intended to follow a trajectory leading to a close flyby of the sun, with a 19-h passage spent within three to four solar radii. Many uses for Starprobe were discussed; in relativity, the plans were to determine perihelion precession, the size of the sun's quadrupole mass moment, and possibly to measure second-order redshift by means of hydrogen-maser clocks mounted on the spacecraft. Despite the short period of flyby, the perihelion precession is large enough to be measurable to fair precision with existing tracking techniques. The drag-free requirement is about 1 pg, difficult to achieve under the conditions of the experiment, but perhaps feasible. The major engineering challenge is to shield the payload against the intense heat of the sun.

An even bolder experiment is the proposal by Bender and Faller[48] to detect long wavelength gravitational radiation by means of laser interferometry between three remote drag-free spacecraft arranged to form the two perpendicular paths of a Michelson interferometer with arms 10^6-km long. The technical challenge of the experiment, discussed by Dr. Faller in his accompanying paper, needs no emphasis. If the experiment could be done, it would rank as one of the most impressive achievements of the space age.

The last experiment, which the author[49] conceived some years ago, is an attempt at a direct measurement of the gravitational spin-spin force. Two concentric masses, one spinning clockwise and one counterclockwise, are placed in polar orbit around Earth with their spin axes parallel to Earth's axis. According to general relativity, there should exist a spin-spin force, analogous to the attraction or repulsion between magnets, of magnitude $F = 24\ G\ J_e\ J_i/c^2\ R^4$, where J_e is Earth's angular momentum, J_i the angular momentum of either spinning body, and R the orbit radius. The force over the pole is a repulsion for a body spinning in the same sense as Earth and an attraction for one spinning in the opposite sense. Assume the two spinning masses are tubes of radii, r_1, r_2, and

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write the results in terms of their peripheral velocities, v_1, and v_2, and Earth's equatorial velocity v_e. Then the acceleration f_1 on body 1 is

$$f_1 = 3.8\ (v_e\ v_1/c^2)(R_e\ r_1/R^2)g \qquad (12)$$

where R_e is the Earth's radius. The acceleration f_2 on body 2 is in the opposite direction. Assuming v_1, v_2 are of order 10^5 cm/s and r_1 r_2 are, respectively, 8 cm and 12 cm, a differential acceleration $(f_1 - f_2)$ is obtained of order 10^{-19} g, modulated at orbital frequency. To measure $(f_1 - f_2)$ to 1%, one would have to be able to measure differential accelerations to 10^{-21} g, that is, with three to four orders-of-magnitude higher precision than the current design goal for the equivalence principle experiment.

The spin-spin experiment is obviously extremely difficult. It is worth thinking about because it takes the investigation of gravitomagnetic phenomena a step beyond the measurement of the gravitomagnetic precession in the gyroscope experiment. It is the only prospect at present for directly testing the spin dependence of such effects.

References

[1]Pound, R.V. and Rebka, Jr., G.A., "Apparent Weight of Photons," Phys. Rev. Lett., Vol. 4, 1960, pp. 337-341.

[1a]Pound, R.V. and Snider, J.L., "Effect of Gravity on Gamma Radiation," Phys. Rev., Vol. 140B, 1965, pp. 788-803.

[2]Roll, P.G., Krotkov, R., and Dicke, R.H., "The Equivalence of Inertial and Passive Gravitational Mass," Ann. Phys., Vol. 26, 1964, pp. 442-517.

[3]Kreuzer, Lloyd, "Experimental Measurement of the Equivalence of Active and Passive Gravitational Mass," Phys. Rev., Vol. 169, 1968, pp. 1007-1113.

[4]Dicke, R.H. and Goldenberg, H.M., "Solar Oblateness and General Relativity," Phys. Rev. Lett., Vol. 18, 1967, pp. 313-316.

[4a]Dicke, R.H. and Goldenberg, H.M., "The Oblateness of the Sun," Astrophys. J. Supp., Vol. 27, 1974, pp. 131-182.

[5]Weber, J., "Detection and Generation of Gravitation Waves," Phys. Rev., Vol. 117, 1960, pp. 306-313.

[5a]Weber, J., "Gravitational Radiation Experiments and Instrumentation," Experimental Gravitation, edited by B. Bertotti, Academic, NY, 1974, pp. 263-279.

[6]Shapiro, I.I., " Fourth Test of General Relativity," Phys. Rev. Lett., Vol. 13, 1964, pp. 789-791.

Downloaded by RMIT BUNDOORA LIBRARY on August 15, 2015 | http://arc.aiaa.org | DOI: 10.2514/4.865824

AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[7]Reasenberg, R.D., Shapiro, I.I., MacNeil, P.E., Goldstein, R.B., Briedenthal, J.C., Brenkle, J.P., Cain, D.L., Kaufman, T.M., Komarek, T.A., Zygielbaum, A.I., "Viking Relativity Experiment: A Verification of Signal Retardation by Solar Gravity," Astrophys. J. Letters, Vol. 234, 1979, pp. 219-221.

[8]Fomalont, E.B. and Sramek, R.A., "Measurements of the Solar Gravitational Deflection of Radio Waves in Agreement with General Relativity," Phys. Rev. Lett., Vol. 36, 1976, pp. 1475-1478.

[8a]Fomalont, E.B. and Sramek, R.A., "The Deflection of Radio Waves by the Sun," Comm. Astrophys., Vol. 7, 1977, pp. 19-33.

[9]Schiff, L.I., "On Experimental Tests of the General Theory of Relativity," Am. J. Phys., Vol. 28, 1960, pp. 340-343.

[9a]Schiff, L.I., "Eötvös Experiment and the Gravitational Red Shift," Am. J. Phys., Vol. 28, 1960, pp. 344-347.

[10]Zacharias cited in notes dated December 22, 1959 by Schiff, L.I. See also Kleppner, D., Vessot, R.F.C., and Ramsey, N.F., "An Orbiting Clock Experiment to Determine the Gravitational Red Shift," Astrophys. & Space Sci., Vol. 6, 1970, pp. 13-32.

[11]Vessot, R.F.C. and Levine, M.W., "A Test of the Equivalence Principle Using a Space-Borne Clock," J. Gen. Rel. and Grav., Vol. 10, 1979, pp. 181-204.

[12]Schiff, L.I., "Motion of a Gyroscope According to Einstein's Theory of Gravitation," Proc. Nat. Acad. Sci., Vol. 46, 1960, pp. 871-882.

[13]Pugh, G.E., "WSEG Research Memorandum No. 11," Weapons System Evaluation Group, The Pentagon, Washington, D.C., Nov. 12, 1959.

[14]Worden, Jr., P.W. and Everitt, C.W.F., "Tests of the Equivalence of Gravitational and Inertial Mass Based on Cryogenic Techniques," Experimental Gravitation, edited by B. Berlotti, Academic, NY, 1974, pp. 381-402.

[14a]Worden, Jr., P.W., "Equivalence Principle in Earth Orbit," Acta Astronautica, Vol. 5, 1978, pp. 27-42.

[15]Van Patten, R.A. and Everitt, C.W.F., "Possible Experiment with Two Counter-Orbiting Drag-Free Satellites to Obtain a New Test of Einstein's General Theory of Relativity and Improved Measurements in Geodesy," Phys. Rev. Lett., Vol. 36, 1976, pp. 629-632.

[16]Pugh, G.E., "WSEG Research Memorandum No. 11," Weapons System Evaluation Group, The Pentagon, Washington, D.C., Nov. 12, 1959, pp. 11-12, 18-19.

[17]DeBra, D.B., "Disturbance Compensation System Design," APL Technical Digest, Vol. 12, 1973, pp. 14-26.

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[17a]Staff of the Guidance and Control Laboratory, Stanford University, Stanford, California, and Staff of the Space Department of the Johns Hopkins University, Applied Physics Laboratory, Silver Spring, Maryland, "A Satellite Freed All But Gravitational Forces," J. Spacecraft Rockets, Vol. 11, 1974, pp. 637.

[18]The concept of the flying drop tower originated in discussions at the Committee for Scientific Uses of Space Station held on Aug. 19-20, 1985 at Stanford University. For details given in the final section, I am indebted to J.M. Reynolds.

[19]For the most up-to-date account, see a series of seven papers in Near Zero: New Frontiers of Physics--Papers in Honor of William M. Fairbank, edited by B.S. Deaver, C.W.F. Everitt, J. Fairbank, and P.M. Michelson, W.H. Freeman Publishers, to be published.

[20]Nikirk, J.R., "Fabrication of an Electronic Suspension Subsystem (ESS) for a Cryogenic Electrostatically Suspended Gyroscope for the Relativity Experiment," Final Report on Contract NAS8-27333, Department of Aerospace and Astronomy, Stanford University, Stanford, CA, Jan. 1983.

[21]Bracken, T.D. and Everitt, C.W.F., "Design of a Gas Spin-up System for an Electrostatically Supported Cryogenic Gyroscope," Adv. Cryo. Eng., Vol. 13, 1968, pp. 168-173.

[22]Lipa, J.A., Nikirk, J.R., Anderson, J.T., and Clappier, R.R., "A Superconducting Gyroscope for Testing General Relativity," Proc. of Low Temperature Physics LT-14-Conference, edited by M. Krusius and M. Vuorio, North-Holland, Amsterdam, 1975, p. 250.

[23]Bull, J. and DeBra, D.B., "Precise Attitude Control of the Stanford Relativity Satellite," Joint Automatic Control Conference, Ohio State University, Columbus, OH, June 1973.

[23a]Bull, J.S., "Precise Attitude Control of the Stanford Relativity Satellite," Ph.D. Thesis, SUDAAR No. 452, Stanford University, Stanford, CA, Mar. 1973.

[23b]J.H. Chen, "Helium Thrustor Propulsion System for Precise Attitude Control and Drag Compensation of the Gravity Probe-B Satellite," Ph.D. Thesis, SUDAAR No. 538, Stanford University, Stanford, CA, Dec. 1983.

[24]Anderson, J.T. and Everitt, C.W.F., "Limits on the Measurement of Proper Motion and the Implications for the Relativity Gyroscope Experiment," W.W. Hansen Laboratories of Physics, Stanford University, Stanford, CA, 1979 (unpublished report).

[25]Everitt, C.W.F., Fairbank, W.M., and Schiff, L.I., "Theoretical Background and Present Status of the Stanford Relativity-Gyroscope Experiment," The Significance of Space Research for Fundamental Physics, Vol. 33, Euro. Space Res. Org. (ESRO) SP-52, May 1971.

Downloaded by RMIT BUNDOORA LIBRARY on August 15, 2015 | http://arc.aiaa.org | DOI: 10.2514/4.865824

AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[26]Duhamel, T., Contributions to the Error Analysis in the Relativity Gyroscope Experiment, Ph.D. Thesis, SUDAAR No. 540, Stanford University, Stanford, CA, Apr. 1984, pp. 31-36.

[27]As indicated in Vassar, R., Breakwell, J.V., Everitt, C.W.F., and Van Patten, R.A., "Orbit Selection for the Stanford Relativity Gyroscope Experiment," J. Spacecraft, Vol. 19, No. 1, January-February 1982, pp. 66-71; for details see Vassar, R., "Error Analysis for the Stanford Relativity Gyroscope Experiment," Ph.D. Thesis, SUDAAR No. 531, Stanford University, Stanford, CA, Mar. 1982.

[28]Lee, T.D. and Yang, C.N., "Conservation of Heavy Particles and Generalized Gauge Transformations," Phys. Rev., Vol. 98, 1955, p. 1501.

[29]Galileo, G., Two New Sciences, translated by H. Crew, and A. De Salvio, Dover, NY, pp. 62f; for a recent assessment, see Stillman, Drake, Galileo at Work, University of Chicago Press, Chicago, IL, 1978, pp. 19-21, 414-416.

[30]Newton, I., Principia, Book II, Section VI, Prop. XXIV, Cor. VII, which contains the first formal definition of equivalence. Book II (Second Edition), Prop XL, Experiments 13, 14 describe investigations including one by Desaguliers in 1719 with lead weight and inflated hog's bladders demonstrating effects of air drag in the Galileo-type experiments.

[31]Eötvös, R.V., Pekár, V., and Fekete, E., "Beitnage zum Gesetze der Proportionalitat von Tragheit und Gravitat," Ann. der Phys., Vol. 68, 1922, pp. 11-16.

[32]Potter, H.H., "Some Experiments on the Proportionality of Mass and Weight," Proc. Roy. Soc (London), Vol. 104, 1923, pp. 588-610.

[33]Worden, Jr., P.W., Proceedings of Third Marcel Grossmann Meeting on General Relativity, edited by Hu Ning, Science Press and North Holland, Amsterdam, 1983, pp. 771-779.

[34]Pugh, G.E., "WSEG Research Memorandum No. 11," Weapons System Evaluation Group, The Pentagon, Washington, D.C., November 12, 1959.

[35]Chapman, P.K. and Hanson, A.J., Proceedings of the Conference on Experimental Tests of Gravitational Theories, edited by R.W. Davies, JPL Tech. Memo No. 33-499, Jet Propulsion Laboratory, Pasadena, CA, 1971, pp. 288-235.

[36]First pointed out by P.K. Chapman in "System Design for an Eötvös Experiment in Earth Orbit," Massachusetts Institute of Technology, Cambridge, MA, 1972, unpublished.

[37]Lense, J. and Thirring, H., "Uber den Einflub der Eigenrotation der Zentralkorper auf die Bewegung der Planeten und Monde nach der Einsteinchen Gravitationstheorie, Phys. Zeits., Vol. 19, 1918, pp. 156-163.

[38]Schaechter, D., Breakwell, J.V., Van Patten, R.A., and Everitt, C.W.F., "Collision Avoidance for Two Counter-Orbiting Polar Satellites," J. Astronaut. Sci., Vol. 24, 1976, pp. 137-146.

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AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[39]Ciufolini, I., "Measurement of the Lense-Thirring Effect on 'LAGEOS' and Another High Altitude Laser Ranged Artificial Satellite," Phys. Rev. Lett., submitted for publication.

[40]Tapley, B.D., Schutz, B.E., and Eanes, R.J., "Station Coordinates, Baselines and Earth Rotation from LAGEOS Laser Ranging: 1976-1984," J. Geophys. Res., 1985, in press.

[41]Carter, W.E., Robertson, D.S., Pettey, J.E., Tapley, B.D., Schutz, B.E., Eanes, R.J., and Lefueng, M. Science, Vol. 224, 1984, pp. 957-961.

[42]Lange, B.O., "The Drag-Free Satellite," AIAA Journal, Vol. 2, 1964, pp. 1590-1606.

[43]Lange, B.O., "The Control and Use of Drag-Free Satellites," SUDAAR No. 194, Stanford University, Stanford, CA, 1964.

[44]Fleming, A.W. and Tashker, M.D., "Final Report on Mass Attraction of TRIAD I/DISCOS," submitted to Johns Hopkins Applied Physics Laboratory under Contract NOW62-0604c, Sept. 1972, SUDAAR No. 445, Stanford University, Stanford, CA, 1972.

[45]DeHoff, R., "Minimum Thrustors Control of a Spinning Drag-Free Satellite, Including Design of a Large Cavity Sensor," SUDAAR No. 497, Stanford University, Stanford, CA, 1975.

[46]Reasenberg, R.M. and Shapiro, I.I., "POINTS, the Planet Finder," BAAS, Vol. 11, 1979, p. 554. Presented at the AAS/DPS Meeting No. 11, Clayton, MO, 23-26 Oct. 1979.

[46a]Reasenberg, R.D., "Microarcsecond Astrometric Interferometry," in Proc. of the Workshop on High Angular Resolution Optical Interferometry From Space, Baltimore, June 13, 1984, edited by P.B. Boyse and R.D. Reasenberg, BAAS, Vol. 16, (3,II), 1984, pp. 758-766.

[47]See papers by Roxburg, I.W., Reasenberg, R.D., Shapiro, I.I., Anderson, J.D., Lau, E.L., Nordtvedt, K., Everitt, C.W.F., DeBra, D.B., and Forward, R.L., A Close Up of the Sun, edited by M. Neugebauer and W. Davies, JPL Publication 78-70, September 1, 1978, pp. 11-80. The idea of using drag-free satellites for a test of perihelion precession seems first to have been made by J. Blamont in a proposal to ESRO in June 1969. See G.M. Israel, Proceedings of the Conference on Experimental Tests of Gravitation Theories, edited by R.W. Davies, JPL Tech. 33-499, 1971, pp. 236-241.

[48]Faller, J.E., Bender, P.L., Hall, J.L., Hills, D., and Vincent, M.A., Proceedings of Colloquium on Kilometric Optical Arrays in Space, Cargese, Corsica, Oct. 1984; also ESA Report SP-226, April 1985, pp. 157-163.

[49]Everitt, C.W.F., "General Relativity and Precision Experiments," Proc. of the International School of General Relativistic Effects in Physics and Astrophysics, Experiments & Theory, edited by Jurgen Ehlers, Max-Planck, Erice-Trapani-Sicil, August 24-Sept. 4, 1977, MPI-PAE/Astro 138, Nov. 1977, p. 118.

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Comments on Gravitation

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In his chapter, Francis Everitt discusses in detail two proposed space-borne gravitational physics experiments. The first, which is known as the Eötvös experiment, asks whether all materials fall at the same rate in a gravitational field; in other words, it tests the "equivalence" of inertial and gravitational mass. The second experiment is Gravity Probe B (alias the Stanford Gyro)--an experiment designed to look for various gravitational "frame-dragging" effects.

Note that, as Everitt discusses, the apparatus most often used for Earth-borne Eötvös experiments has been the torsion balance--a vertical "torsion" wire supporting a horizontal beam. This type of balance, invented by Charles Augustin Coulomb in France (about 1777) and developed independently and at about the same time by the Rev. John Michell in England, removes gravity as a factor in those gravitational, electrostatic, and magnetic experiments in which it was used. By "defining" the horizontal plane, and thereby producing a "zero-gravity environment," it provides the basis to (torsionally) sense very weak forces.

The version of the Eötvös experiment presently being developed at Stanford[1] is designed for ultimate use in a space environment. As Everitt notes, it is a linear, as opposed to a torsion, experiment because a linear "balance" is less sensitive to the effects of gravity gradients. This introduces, however, a distinct tilt sensitivity into the present ground-based version. The primary advantages of doing this experiment in space are 1) a larger driving acceleration (780 cm/s^2 at 300 n.mi. alt) rather than Earth's free-fall acceleration toward the sun (about 0.6 cm/s^2); and 2) the information appears at a higher frequency (100 min rather than 24 h). Vibration or mechani-

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cal disturbances in a free-flying, drag-free satellite are potentially less than disturbances on the ground; however, this is not true of the shuttle. The shuttle's acceleration environment is typically 10 times worse than Earth's surface. Thus, the gain for a (preliminary) shuttle-carried space experiment comes not through a low-gravity environment, but rather (primarily) from the potential three orders-of-magnitude greater effect as a result of the larger acceleration that exists in orbit.

The second gravitational physics space experiment Everitt discusses is Gravity Probe B.[2] (Gravity Probe A was the rocket-borne Smithsonian "clock" experiment.) Gravity Probe B is designed to test various frame-dragging effects; although simple in concept, its implementation requirements are formidable--a fact hinted at by this experiment's 20-year development time. For this experiment, the low gravity of space is essential to avoid perturbing torques on the gyroscopes. Although a shuttle test can serve to verify the overall systems operation, a subsequent flight in a drag-free satellite will be required to achieve the desired scientific results.

A few points warrant review. Note what it is that space offers to these experiments. To the first (Eötvös) experiment, it offers 1) an approximately 1,000 times larger potential effect and 2) a somewhat higher frequency for any signal. Were this experiment to be free-flown, the reduced-vibration environment would also be useful. For the second experiment, although there are a number of advantages to be gained, the primary one--and the one which will be realized only when the apparatus is free-flown--is the reduced gravity (and, equivalently, vibration) environment that would avoid extraneous torques on the four frame-drag-sensing gyros.

In each of these experiments, one is sending a "point" apparatus into space to measure or sense some particular effect. In some cases, space also can be considered as contributing part of the apparatus. An example of this is the recent suggestion by Ignazio Ciufolini.[3] He proposes to use the presently orbiting LAGEOS satellite with a similar high-altitude satellite--with the appropriate orbital parameters--in combination with a laser ranging from the Earth to provide another method of looking for these two gravitational frame-dragging effects. Here the apparatus "size" (two satellites plus monitoring ground stations) is of the order of 12,000 km. Although this approach is probably only capable of yielding a 10-20% accuracy (Gravity Probe B is designed to be an order of magnitude more accurate), this highly complementary approach could provide a somewhat less accurate verifica-

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tion of these magnetogravitational effects. What is being proposed takes particular advantage of the dramatic improvements that have occurred over the past 20 years in satellite tracking that uses ground-based laser-ranging systems.

Finally, a brief comment is required on the proposed laser heterodyne gravity wave interferometer.[4] This proposed experiment, which involves a cluster of three spacecraft placed in nearly circular 1-year Earth-like orbits around the sun, would serve to both complement and extend in frequency range the ground-based bar and interferometer gravity wave systems presently being developed. Possible baselines for this space-borne Michelson-type interferometer range from 10^5 km to 10^6 km. Although the sources of gravitational waves that can be studied with ground-based detection are of major scientific importance, there is general agreement that the most valuable astronomical information will ultimately come from studies of longer period gravitational waves from events involving supermassive black holes or galactic formations. It is these events that can be observed only in the seismically benign (low-gravity) environment of space. In space, the fundamental "microseismic" background results from planetary (gravitational) perturbations and occurs at periods (order of 1 year) appropriate to these motions. Carefully designed drag-free satellites will be required to shield the individual test masses against other perturbations resulting from solar radiation, solar wind, and other forces. Earth-based gravity wave detectors suffer from a very sharp (about 10 Hz) cutoff in sensitivity on the low-frequency end of the spectrum due to ground motion and time-varying local gravitational disturbances, and these serve to limit the frequency window of ground-based observing systems.

In summary, although ground-based experiments in gravitational physics can be and still are being done very profitably, for some experiments to reach the required sensitivity and/or for others to permit observing in the most useful frequency range, space is becoming an increasingly necessary arena for the testing of gravitational theories.

References

[1]Everitt, C.W.F. and Worden, P.W., "Final Report: A Preliminary Study of a Cryogenic Equivalence Principle Experiment on Shuttle," NASA Report 33796, 1985.

[2]Levi, Barbara G., "Orbiting Gyro Test of General Relativity," Physics Today, Vol. 37, May 1984, pp. 20-22.

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[3]Ciufolini, Ignazio, "Measurement of the Lense-Thirring Effect on 'LAGEOS' and Another High Altitude Laser Ranged Artificial Satellite," The Center for Relativity and Physics Department, University of Texas, TX. Submitted to Phys. Rev. Letters.

[4]Faller, J.E., Bender, P.L., Hall, J.L., Hils, D., and Vincent, M.A., "Space Antenna for Gravitational Wave Astronomy," Proceedings of Colloquium on Kilometric Optical Arrays in Space, Cargese, Corsica, October 1984; also ESA Report SP-226, April 1985, pp. 157-163.

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Opportunity for Academic Research in a Low-Gravity Environment: Crystal Growth

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Introduction

Progress in advanced and projected solid-state-device technology is increasingly dependent on the availability of semiconductor crystals with a high and controlled degree of chemical and crystalline perfection. Evidence indicates that complications related to gravity are largely responsible for the present failure to achieve theoretical perfection limits in crystals; they are also accountable for the gap between theory and experiment and the thus far heavy reliance on empirical procedures in crystal growth.

It is now firmly established that diligent experimentation in a reduced-gravity environment, based on related meaningful ground-based research, can significantly enhance the scientific framework for crystal growth and thus provide for improved capabilities of crystal-growth technology. Such activities can, moreover, provide the foundation for a rational assessment of the potential of industrial space processing activities. The incorporation of a microgravity environment into the arsenal of advanced research capabilities is no longer a question of principle but of time. The scope of related research and development activities demands the participation of academic institutions and is expected to lead to intensive research interaction among academic, industrial, and government institutions.

A comparative analysis was conducted of the effectiveness of a reduced-gravity environment and magnetic fields for the stabilization of semiconductor melts during

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crystal growth. Magnetic fields of up to about 4 kilo-Gauss (kG) fail to even approach the degree of melt stabilization observed in a reduced-gravity environment.

Crystal Growth and Solid-State Technology

It is truly a paradox that industrial crystal growth of semiconductor systems, the basis for all of solid-state-device technology, is still without an adequate scientific foundation and, thus, by necessity, conducted on a largely empirical basis. The benign neglect afforded crystal growth until quite recently can be attributed to three primary factors. 1) Property requirements of silicon for medium- and large-scale device integration were met by the established growth procedures; 2) yield affecting materials deficiencies can be overcome by the use of epitaxy, changes in device architecture, and through built-in redundancy of devices; and 3) research efforts aimed at quantifying the growth and segregation behavior in industrial-scale systems have been of limited success, primarily because of major complications in the heat- and mass-transfer characteristics caused by gravity-induced convection phenomena.

Property requirements for silicon became noticeably more stringent as wafer diameters increased to exceed 100 mm and as (with the arrival of very large-scale integrated circuitry [VLSI]) the linear device dimensions approached the effective dimensions of crystal defects. Growth-related deficiencies in bulk silicon today constitute a serious problem for the fabrication of field-effect transistors (FETs), of charge storage devices, and of focal plane arrays, which, for that reason, can as yet only be produced at very low yield and with severely restricted linear dimensions. Of even greater concern is the mounting evidence that the adverse side effects of bulk deficiencies on device performance and yield increase with the increasing scale of device integration. Furthermore, U.S. industry is concerned about foreign competition, which has in recent years assumed leadership in the electronic materials sector.

It is also of interest to consider compound semiconductors. Despite their superior and versatile electronic and opto-electronic properties, they have as yet not even approached their full potential in device application, largely because of an inability to produce them with the required degree of crystalline and chemical perfection. Experimental evidence strongly suggests that the advancement of compound semiconductor device technology will be controlled by advances in growth technology.

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The mandatory resort to empiricism for industrial melt growth of semiconductors can be attributed to several complicating factors that negate the applicability of the existing scientific framework.

- All conventional melt growth configurations for electronic and opto-electronic materials require the application of thermal gradients across the phase boundary; the axial and/or radial components of these gradients are destabilizing in 1-g environment and provide driving forces for free convection in all fluid phases involved. These driving forces increase with the freezing point and the physical dimensions of the system, generating nonsteady flows in configurations of technological interest. Most growth processes are therefore subject to nonquantifiable, time, and spatially varying heat- and mass-transfer conditions, which in recent years have been found to be directly or indirectly responsible for a vast majority of bulk deficiencies in single crystalline electronic materials.
- Melt containment leads to serious adverse side effects, including contamination, heterogeneous nucleation, changes in heat-transfer characteristics, and the establishment of mechanical stresses arising from the interaction between the forming solid and the rigid containment. In some instances, the containment of corrosive high-temperature melts constitutes an almost intractable problem.
- Complications in the critical heat- and mass-transfer characteristics of growth systems, arising from the combined effects of confinement and gravity-induced nonsteady convection, seriously impede the meaningful application of theory aimed at understanding and optimizing the crystal-growth process.

The tenuous nature of the science base for melt growth of semiconductors is clearly demonstrated in as yet unresolved controversies pertaining to the physical nature of the dominating driving force for turbulent melt convection in the technologically most important Czochralski crystal pulling process.

With mounting evidence that the adverse effects of substrate deficiencies on device fabrication increase with decreasing device dimensions, the necessity for a meaningful science base in support of the currently practiced

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proprietary empiricism in crystal growth is generally appreciated. Major corporations have, in this context, examined the potential of a reduced-gravity environment. They are apprehensive about their approach primarily because of "time-in-space constraints," which do not allow for a return of investment within an acceptable time frame.

It is important to recognize that, by and large, industry's expectations from microgravity research for industrial crystal growth have changed noticeably since the publication of the Scientific and Technological Aspects of Materials Processing in Space (STAMPS) report.[1] With increasing evidence of adverse side effects from deficient bulk materials and with steadily mounting foreign competition, industry can be expected to actively participate in collaborative efforts aimed at establishing the potential of materials processing in a reduced-gravity environment.

Crystal Growth and Academia

Academic crystal-growth research of semiconductor systems in the United States traditionally has been very limited in scope and restricted to melt and solution growth of systems with small dimensions and with relatively low melting points. Research carried out in a few materials science and electrical engineering departments, funded largely by DOD agencies, reflects industry's benign neglect. The academic research volume in crystal growth increased noticeably when NASA decided to focus on basic research deemed necessary for a meaningful exploration of the potential of a reduced-gravity environment. This thrust gained momentum when controversial experimental results obtained from experiments in space attracted scientists and engineers from peripheral disciplines. The resultant interdepartmental collaborations among materials science, mechanical, chemical, and electrical engineering departments are now recognized as providing exceptional strength to academic research in crystal growth and forming the basis for meaningful and expanding interaction with industry.

Established trends in engineering education suggest that electronic materials processing and, more specifically, crystal growth and characterization of semiconductor systems will emerge as a viable study and research option in graduate schools. This activity is expected to expand rapidly from the exclusive realm of abstract theory to include engineering-oriented applied science aimed at narrowing the gap between theory and experiment. Exploration of the solidification behavior of systems at less than 1-g values should be considered as a basic scientific

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issue and should be a subject of concern for academia. A microgravity environment can, moreover, be expected to provide for crystal-growth conditions under which fundamental complications deriving from gravity-induced nonsteady convective flows can be avoided. Such research, theoretical and experimental, will assuredly contribute in a major way to the establishment of elusive relationships among experimentally controllable growth parameters, growth behavior, and defect formation during solidification. Substantial involvement of academia in processing-oriented space research thus emerges as an activity that has not only educational value, but, moreover, may lead to meaningful technology transfer.

Crystal Growth and NASA's Microgravity Research Program

Exploration of the potential of a reduced-gravity environment for crystal growth of semiconductor systems has been pursued by NASA since the first opportunity arose to perform long-duration experiments in space. Given the benign neglect afforded semiconductor processing by high-technology corporations, NASA's program relied heavily on university participation. The shortcomings of early space experiments have been analyzed in detail by the STAMPS Committee. Although criticism of early experiments was appropriate, it appears equally appropriate to acknowledge the significant advances made. Research on melt stabilization led to the development of Magnetic Czochralski Pulling (MCZ), now commercially applied to growth of large-diameter silicon. This approach to the suppression of turbulent melt convection is now recognized as potentially even more significant for achieving improved crystalline and chemical perfection in compound semiconductors such as gallium arsenide, indium phosphide, and cadmium telluride. The use of heat pipes for the establishment of axisymmetric thermal fields in Czochralski systems led to the virtual elimination of rotational dopant striations and of radial segregation in small-diameter semiconductor crystals with melting points of less than 1000°C. Current-induced interface demarcation during crystal growth, developed for quantitative studies of the microscopic growth behavior of systems in a reduced-gravity environment, now emerges as the most reliable analytical approach to quantitative studies of melt growth. The same technique, applied to liquid phase epitaxial systems, has led to the evolution of current-controlled epitaxy.

By applying approaches developed for space research, Bridgman growth, which for decades was considered the

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most convenient means for the production of semiconductor single crystals with small diameters, was for the first time quantitatively investigated. This study resulted directly in the development of computer-controlled, heat-pipe-based growth systems with quantifiable thermal boundary conditions and with theoretically predictable growth and segregation characteristics. Modeling of heat and mass transfer in crystal-growth configuration became, for the first time, an exercise that could be subjected to meaningful quantitative experimental analysis.

Opportunities for Academic Research

Although progress has been made in crystal-growth technology during the last decade, the rate of advance is exceeded by the rate at which property requirements become more stringent as a result of advances in device technology. Residual crystalline and chemical deficiencies in semiconductor matrices today likely impose greater limitations to device technology than they did a decade ago.

Given a deficient theoretical foundation, needed advances in crystal growth will be both costly and time consuming, particularly because the industrial research base has been eroded. One must again note the nature of the complications considered responsible for deficient semiconductor processing: gravity-induced perturbations in critical heat- and mass-transfer phenomena account largely for the current inability to bridge the gap between theory and experiment in crystal growth and the inability to achieve or even approach theoretical limits of crystalline and chemical perfection in electronic and opto-electronic materials. The complex issues of concern demand complementary input from chemical engineering (mass transport), mechanical engineering (heat transport), and control theory not readily available in industrial semiconductor processing but available in some advanced universities and technological institutions.

The recent emergence of more intensive university-industry-government interaction strongly suggests a collaboration in which academic research predominantly focuses on broadening the science base for crystal growth, and industry implements the corresponding technology transfer.

The University Space Research Association (USRA) recently submitted to NASA recommendations that analyze the opportunities related to microgravity research. In context, a thorough experimental verification of the potential of a reduced-gravity environment is considered in the national interest, with direct benefits deriving primarily

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from the following:

- The elimination or significant reduction of buoyancy-driven natural convection (for substantial periods of time) in fluid phases under conventional and nonconventional crystal-growth configurations
- The possibility of conducting liquid-solid phase transformations involving unconfined or nearly unconfined melts and solutions
- The possibility of conducting well-defined growth experiments aimed at elucidating the formation of growth-related electrically and/or optically active defects, establishing their identity, and achieving their control
- The evolution of nonconventional crystal-growth configurations
- The reduction or practical elimination of gravitationally driven sedimentation in fluid phases
- The establishment of a reference base for advanced modeling approaches to crystal growth
- Growth of small quantities of materials with a presently unachievable degree of purity and perfection to serve as property reference standards
- The determination of physical (transport) constants

The absence of a comprehensive understanding of crystal growth as practiced precludes categorical statements concerning the potential of a reduced-gravity environment. However, it has been demonstrated on the one hand that turbulent melt convection during growth leads to a serious deterioration of critical bulk properties of electronic materials and, on the other hand, through preliminary experiments in space, that diffusion-controlled growth (absence of convective interference) can be achieved in a reduced-gravity environment of g-levels ranging from 10^{-4} to 10^{-6}. Space experiments established, moreover, that surface-tension-driven convection (predicted by theory to be a dominant factor during unconfined crystal growth in a reduced-gravity environment) can be controlled.

In any attempt to assess the potential in a microgravity environment for materials processing, there are unavoidable elements of uncertainty related to the complexity of the crystal-growth process, the tenuous nature of the existing theoretical framework, and the limited experimental data on growth behavior in space. It is therefore not inconceivable that the pursuit of as yet

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unidentifiable phenomena in space may fundamentally affect the advancement of existing, and the evolution of new, approaches to crystal growth.

Crystal Growth and Melt Stability

The degree of crystalline and chemical perfection achievable in semiconductors by conventional growth technology is, as yet, significantly removed from theoretical limits. The primary obstacles to the realization of materials with designed properties has been traced to 1) the lack of a viable, quantitative theoretical framework for crystal growth and 2) gravitational interference, which results in both nonsteady-state convection within all fluid phases involved and in the requirement for charge confinement with related contamination and heat-transfer problems.

The inability to even approach theoretical degrees of crystalline perfection was until recently not considered a drawback because critical property requirements for conventional device technology could be met through established procedures. Identifiable materials deficiencies were overcome through epitaxy, alterations in device architecture, and/or built-in device redundancy. A fundamental change in basic property requirements of semiconductors used for device fabrication became apparent with the advent of very large-scale device integration and the development of highly structured and composition-sensitive systems such as charge-transfer devices.[2] This change, which entailed more stringent composition and defect control, is, if anything, magnified in the manufacture of compound semiconductor devices. At present, property requirements for some advanced and projected device technology are only marginally met in available materials, and desired progress in device development appears linked to improvements in materials perfection and property control during processing.

With the identification of the primary causes for defect formation during melt growth of single crystals, the exploration of a reduced-gravity environment for semiconductor processing was a logical step.[3] Preliminary space experiments involving growth of doped semiconductors in gradient freeze configurations (Fig. 1) did provide significant data, which stimulated a broad-based reexamination of the existing scientific framework for melt growth and segregation. They failed, however, to establish the potential of space processing. Of particular concern is the finding that radial dopant segregation during melt growth in space[4] can exceed that encountered during growth on

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Earth by more than one order of magnitude. Also disputed is the magnitude of the convective driving force provided by the temperature and concentration dependence of the surface tension of free semiconductor melts in growth configurations.

Theoretical consideration of the results obtained in space experiments indicates a significantly increased sensitivity of growth and segregation to heat-transfer conditions. Also predicted by theory, though not confirmed experimentally on Earth, is the dependence of the wetting behavior of semiconductor melts on the chemical nature and concentration of dopant elements. The wetting conditions are of concern insofar as they affect heat transfer to and from the melt and, on solidification, can lead to large mechanical stresses and thus to the generation of a massive dislocation network.

An alternative to operation in a reduced-gravity environment for melt stabilization is suggested by magnetohydrodynamics: the application of vertical or horizontal magnetic fields.[5-7] Experimental studies with magnetic Czochralski growth[8-10] indicate that both transverse and axial fields will, on exceeding a critical value, shift the

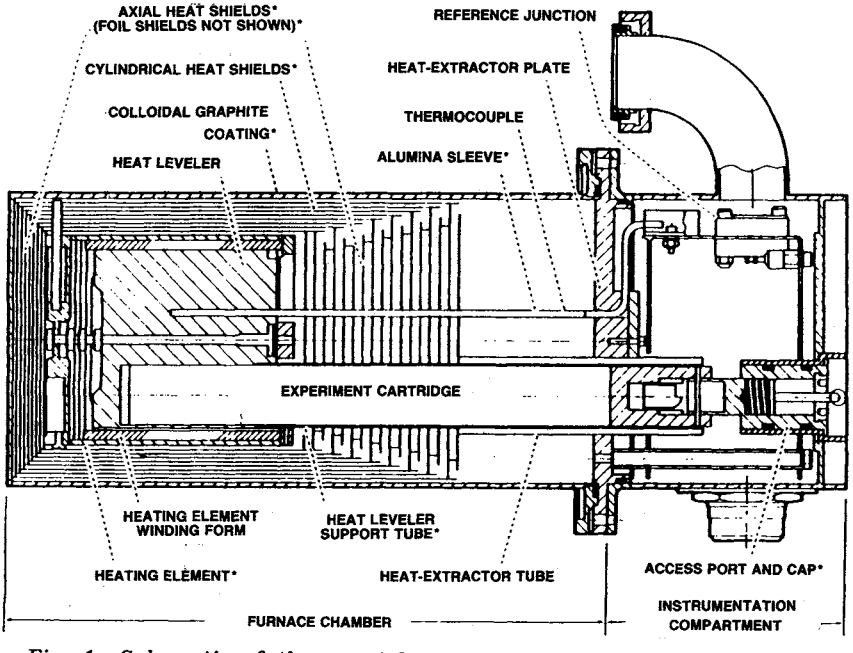

Fig. 1 Schematic of the crystal growth system used for experimentation in reduced-gravity environment. (Asterisks indicate design modifications.)

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fluid dynamic melt instability from the time-dependent turbulent to the time-independent laminar flow regime.

The authors have conducted experiments to determine for vertical Bridgman growth the degree of control achievable with transverse and axial magnetic fields over the thickness of the momentum boundary layer at the crystal-melt interface. It was of interest to establish through comparative analysis the extent to which segregation control, achievable in a reduced-gravity environment, can be approached by magnetic melt stabilization on Earth.

Experimental Work

All growth experiments conducted to the control achievable with magnetic fields were carried out in the multipurpose gradient freeze facility used during the Apollo-Soyuz Test Project (ASTP)[4]; the applied axial and transverse magnetic fields ranged from zero to 1.8 and zero to 3.0 kG, respectively.

Sample Preparation. The charges used for the experiments consisted of gallium-doped germanium crystals grown by the Czochralski technique from melts doped to 10^{20} atoms/cm^3 using seeds of <100> and <111> orientation. The charge crystals were centerless ground to a 1-cm diam and cut to a length of 5 cm. The seed segments of 2-cm length were ground to a 0.8-cm diam to permit attachment of cup-shaped graphite electrodes for growth interface demarcation.[4] Prior to encapsulation, the crystal samples were etched with modified CP-4[4]; the quartz ampoules used for encapsulation were etched in hydrofluoric acid (HF) and, like the crystals, subsequently rinsed with deionized water and methanol. The ampoules were enclosed in a stainless steel cartridge under a pressure of 2 psig argon after repeated evacuation and flushing.

Melting and Growth Procedure. The growth experiments were performed in the MA 010 system,[4] modified to provide for a constant heat-sink temperature. The furnace was positioned vertically, and partial remelting of the charge crystal was accomplished by raising the hot-zone temperature to 1150°C over a period of 10 h, while maintaining the cold-zone heat extractor plate at a fixed temperature of less than 100°C. In this thermal configuration, a temperature gradient of 50°C/cm was achieved in the gradient zone with the seed-melt interface located 1.1 cm from the cold end of the crystal. For thermal equilibration, the hot zone was maintained at temperature for 2 h, and controlled regrowth of about 10 μm/s, which asymp-

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totically approached 20 μm/s, was achieved through a programmed cooling rate (2.4°C/min) of the hot zone. For growth-interface demarcation, current pulses (20 A) of 55-msec duration were transmitted across the crystal-melt interface at fixed time intervals.

Analytical Procedure. Growth and segregation analyses were performed as follows. All regrown crystals were cut with a diamond saw along the growth direction to position in 2-mm thick slices the crystal axis at the surface of the specimen when prepared for analysis. For single-point spreading resistance analyses, the back side of the crystal slices was alloyed with 50/50 indium-tin solder and mounted on standard round brass disks. The mounted specimens were lapped with 5-μm garnet and subjected to chemical/mechanical polishing using Nalcoag 1030 solution on a Rodel #204 PSA II polishing pad. The polished samples were etched with agitation for 10 s in a high-resolution striation etch consisting of equal parts HF, CH_3COOH, and H_2O_2. For quantitative segregation analyses, single-point spreading resistance measurements at spacings of 10 μm (microsegregation) and 100 μm (macrosegregation) were performed on the etched specimen, and the corresponding microscopic growth rates were determined with a filar eyepiece using interference contrast microscopy. After correction for external resistance in the measurement circuit, the spreading resistance data were converted to resistivities by using probe calibration factors obtained through Hall-effect measurements. Carrier concentrations were determined from the resistivity data, employing a curve fit to Cuttrass's curves.[11]

Results and Discussion

Heat-Transfer Considerations

Inherent in the design of the growth system is the existence of a radial thermal gradient at all positions of the crystal-melt interface. Because of the geometry of the system, which provides for three growth cavities, the prevailing radial gradients are, moreover, asymmetric and are subject to change as the solidification isotherm (the location of the crystal-melt interface) is, under the imposed cooling rate, forced into the hot-zone region. These basic deficiencies in the thermal configuration are reflected in the morphology of the crystal-melt interface (revealed by interface demarcation) and in its change during growth (Fig. 2). A comparison of the morphological characteristics

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observed in this study with those of earlier studies in the same system reveals a pronounced resemblance for growth experiments conducted 1) in the presence and absence of magnetic fields, 2) in 1-g and microgravity environments, and, 3) prior to and following modifications involving furnace rewinding. It is therefore concluded that the heat-flow characteristics in the crystal-melt interface region that control the growth-interface morphology are dominated by the geometry and heat-transfer characteristics of the thermal gradient region.

Microscopic growth-rate analyses based on the measurement of spacings between successive interface demarcations indicate, for a controlled cooling rate of the hot zone (2.4°C/min), a transient growth behavior that is virtually identical with that observed in earlier experiments. The rate of growth increases rapidly at the beginning and approaches a value of about 20 μm/s after a growth distance of 2 cm. The effect of an applied axial magnetic field of 1.8 kG on the microscopic growth beha-

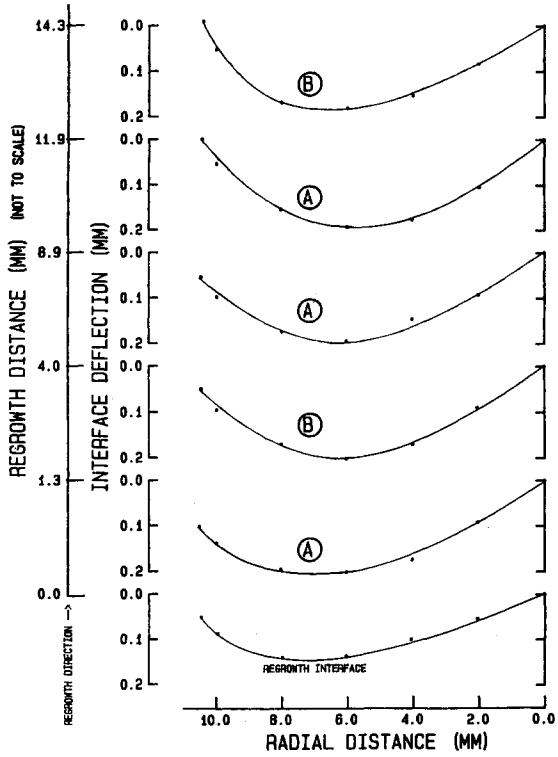

Fig. 2 Crystal-melt interface morphology as determined by interface demarcation for various distances from regrowth interface.

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vior is found to be significant. As seen in Fig. 3, axial field application results in a noticeable decrease of the (radially averaged) microscopic rate of growth, which after 2 cm of regrowth approaches a value of 10 μm/s as compared with 20 μm/s in the complete absence of an applied field. Although the mechanism through which the magnetic field affects the growth rate is as yet unknown, the results appear consistent with a field-controlled increase in the axial thermal gradient. This behavior is of interest

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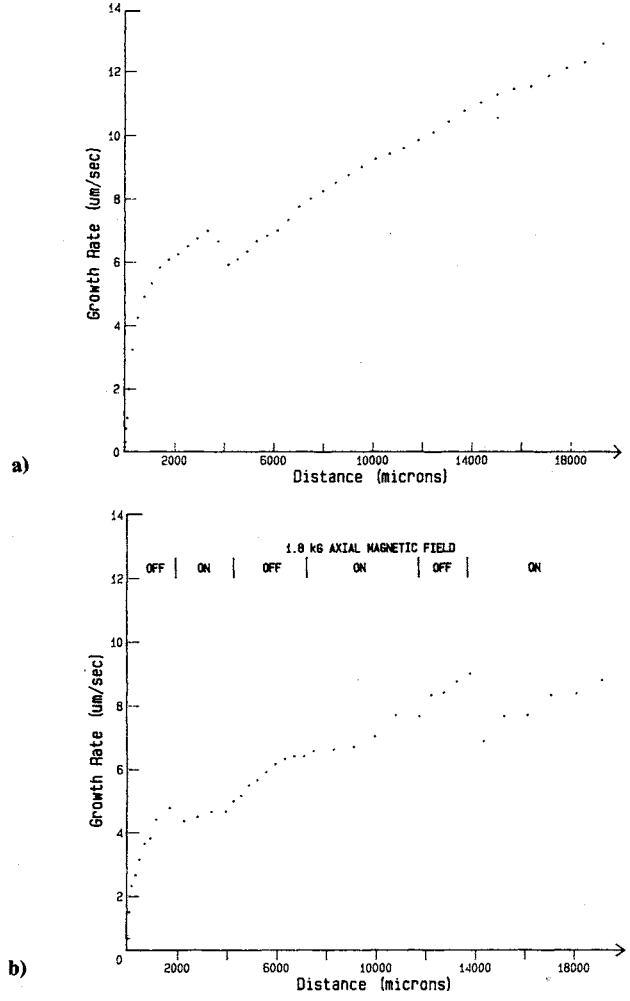

Fig. 3 Microscopic axial growth rate profiles of germanium crystals for A) conventional growth and B) magnetic (1.8 kG) field stabilized growth.

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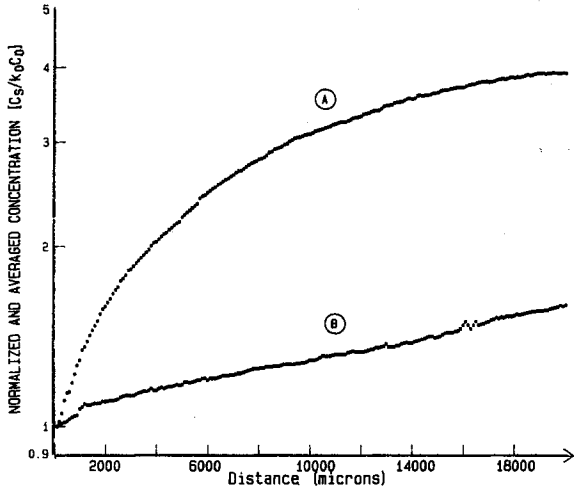

Fig. 4 Averaged and normalized (C_s/k_oC_o) axial charge carrier concentration profiles; A) ASTP results[3] and B) present study without magnetic melt stabilization.

insofar as it differs from that observed in a reduced-gravity environment, which was reported as not measurably different from that encountered under 1-g conditions.

Segregation Analysis. To provide for a meaningful comparative analysis of axial macrosegregation during growth under the various conditions of concern, compositional diagrams, computed from longitudinal spreading resistance scans and radially averaged, were normalized with k_oC_o.

For conventional regrowth (Fig. 4), the presently observed macrosegregation is found to replicate well that reported earlier. Axial segregation during growth in the presence of transverse and axially aligned magnetic fields of 3.0 and 1.8 kG, respectively, (Fig. 5) indicates only a small effect of the applied field. The data suggest that the applied field, regardless of orientation, increases rather than decreases segregation. Considering that the macrosegregation analysis for the cylindrical crystal is based on a limited number of scans within one plane, the observed deviation from standard behavior must be taken as not significant. It is of interest to examine a peripheral composition scan for growth during which a transverse field of 3 kG was intermittently applied (Fig. 6). Contrary to expectation, the data suggest a pronounced drop in dopant incorporation (i.e., increased segregation) with the application of the field. The field effect becomes clearer

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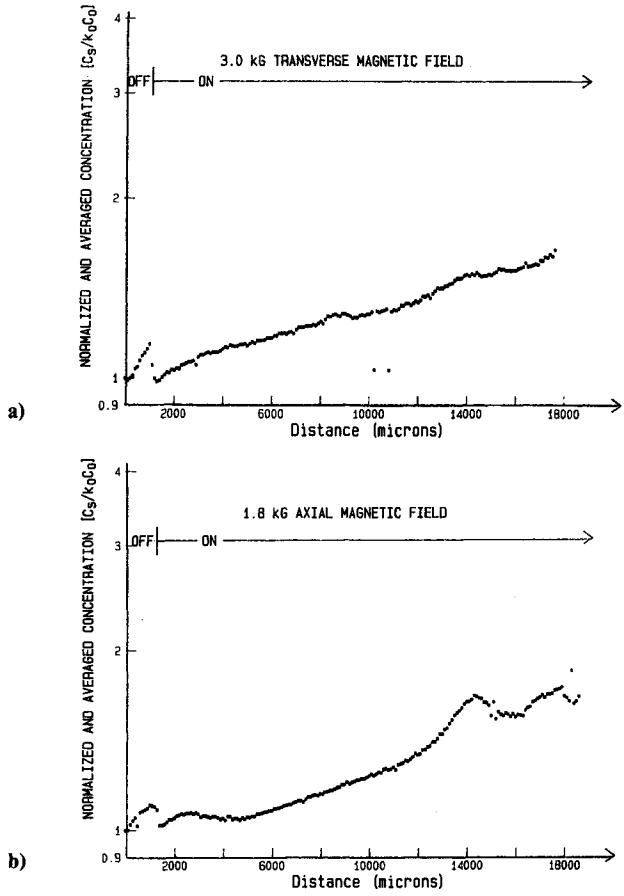

Fig. 5 Averaged and normalized axial charge carrier concentration profiles for A) 3.0 kG transverse magnetic field and B) 1.8 kG axial magnetic field. Time line indicates activation of magnet.

when considering three longitudinal scans, left-center-right, along an axial crystal slice that contains the growth axis (Fig. 7). These data reveal that the presence of a magnetic field leads to radial solute redistribution that results in pronounced local changes of dopant incorporation without substantially affecting the radially averaged axial macrosegregation behavior (Fig. 5). Furthermore, they point out limitations associated with two-dimensional segregation analyses for three-dimensional systems. A further complication of growth and segregation arises from electrical growth interface demarcation in the presence of magnetic fields. This effect is the subject of an ongoing investigation.

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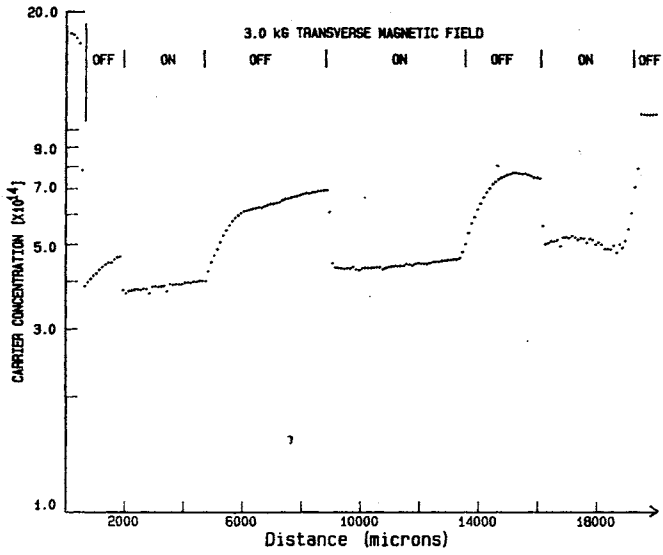

Fig. 6 Peripheral (axial) charge carrier concentration profile for a crystal grown with an applied transverse magnetic field (3.0 kG).

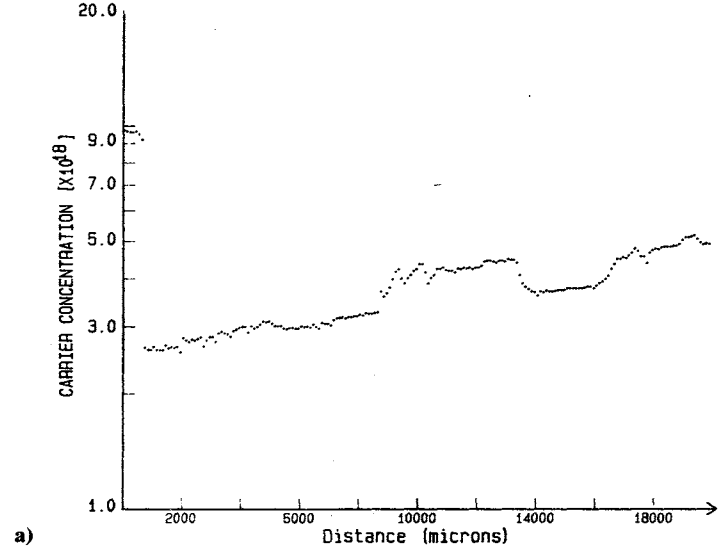

Fig. 7 A) peripheral (left), C) peripheral (right), and B) central charge carrier concentration profiles for crystal grown with an applied axial magnetic field (1.8 kG) in the facility depicted in Fig. 1.

(cont.)

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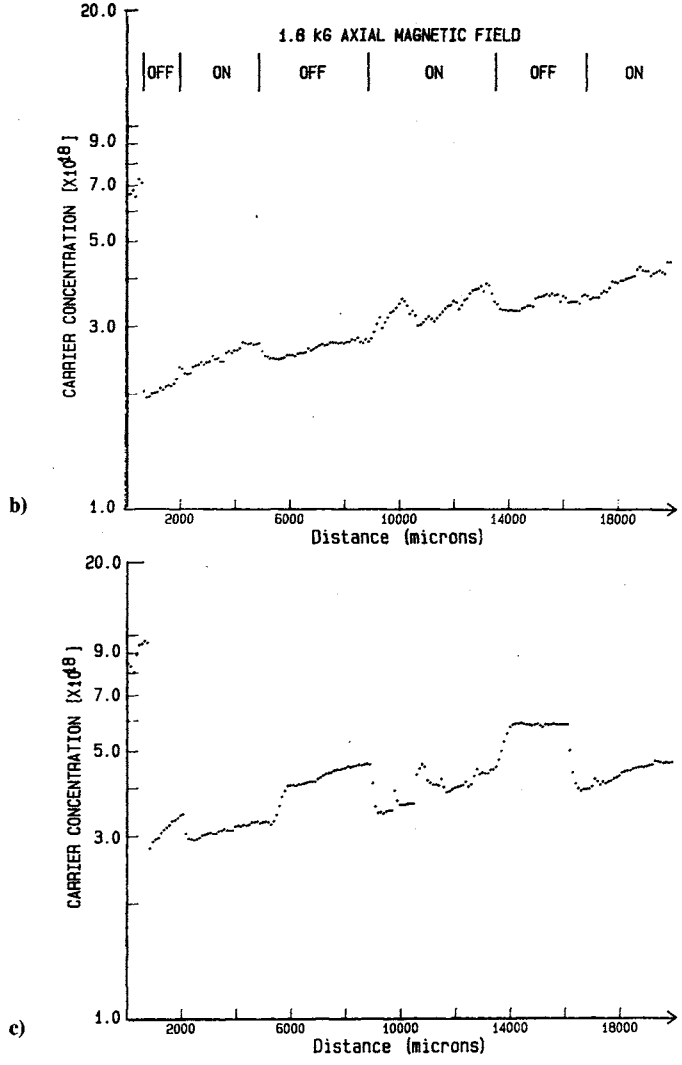

Fig. 7 A) peripheral (left), C) peripheral (right), and B) central charge carrier concentration profiles for crystal grown with an applied axial magnetic field (1.8 kG) in the facility depicted in Fig. 1.

Summary and Conclusions

The effects of both axial and transverse magnetic fields of 1.8 and 3.0 kG, respectively, on segregation during growth in vertical Bridgman configuration were investigated. It was found that axial macrosegregation is

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not noticeably decreased by this procedure. This finding suggests that the effectiveness of magnetic fields for damping convective melt flows already in the laminar regime, as encountered in Bridgman growth, is small. The application of magnetic fields is found to affect substantially, however, the radial solute redistribution. This effect is attributed to changes in convective melt-flow patterns and to related local changes in the thickness of the solute boundary layer at the crystal-melt interface. The reported experimental results suggest that convective flow suppression in semiconductor melts through axial and transverse magnetic fields has limitations that make it unlikely to achieve growth conditions on Earth with k_{eff} approaching unity. Experimentation with crystal growth in the presence of magnetic fields should therefore be considered as a complementary precursor to rather than a substitute for experimentation in a reduced-gravity environment.

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References

[1]STAMPS Committee, Report of the Committee on Scientific and Technological Aspects of Materials Processing in Space, National Academy of Sciences, Washington, DC, 1978.

[2]Jastrzebski, L., "Defects in Silicon Substrates," Microelectronics Measurement Technology Proceedings 1981, Benwill Publishing Corp., Boston, MA, 1981, pp. V1-V14.

[3]Witt, A.F., Gatos, H.C., Lichtensteiger, M., Lavine, M.C., and Herman, C.J., "Crystal Growth and Steady-State Segregation Under Zero Gravity: InSb," J. Electrochem. Soc., Vol. 122 (2), 1975, pp. 276-283.

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[4]Witt, A.F., Gatos, H.C., Lichtensteiger, M., and Herman, C.G., "Crystal Growth and Segregation Under Zero Gravity: Ge," J. Electrochem. Soc., Vol. 125 (11), 1978, pp. 1832-1840.

[5]Utech, H. and Flemings, M.C., "Elimination of Solute Banding in Indium Antimonide," J. Appl. Phys., Vol. 37, 1966, pp. 2021-2024.

[6]Langlois, W.E. and Ki-Jun, L., "Digital Simulation of Magnetic Czochralski Conditions for Silicon Growth," IBM J. Res. and Dev. Vol. 27 (3), 1983, pp. 281-284.

[7]Oreper, G.M. and Szekely, J., "The Effect of a Magnetic Field on Transport Phenomena in a Bridgman-Stockburger Crystal Growth," J. Crystal Growth, Vol. 67, 1984, pp. 405-419.

[8]Witt, A.F., Herman, C.J., and Gatos, H.C., "Czochralski-Type Growth in Transverse Magnetic Fields," J. Mat. Sci., Vol. 5, 1970, pp. 822-824.

[9]Kim, K.M., "Suppression of Thermal Convection by Transverse Magnetic Field," J. Electrochem. Soc., Vol. 129 (2) 1982, pp. 427-429.

[10]Hoshikawa, K., "Czochralski Silicon Growth--the Vertical Magnetic Field," Jap. J. Appl. Phys., Vol. 21 (9), 1982, pp. L545-L547.

[11]Cuttriss, D.B., "Relation Between Surface Concentration and Average Conductivity in Diffused Layers in Germanium," Bell Sys. Tech. J., Vol. 40, 1961, pp. 509-521.

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Comments on Crystal Growth

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It is perhaps easier to critique than to create; however, having the utmost respect for Dr. Witt, who has personally contributed pioneering, significant, and excellent research on growth from the melt of semiconductor crystals in space, the present author is faced with a difficult task. Having little argument with the facts as stated by Dr. Witt in regard to the technical aspects of this specialized subject, this author shall concentrate on putting Dr. Witt's contribution in a broader perspective, specifically with respect to

- o The role of low-gravity crystal growth as catalyst
- o The nature of convection as culprit
- o A broader class of crystalline materials and phenomena
- o The role of NSF

The Role of Low-Gravity Crystal Growth as Catalyst

One of Dr. Witt's recurring themes may be paraphrased as follows: for various reasons, including the proprietary and business nature of semiconductor growth in industry (i.e., if the present recipe works or can be circumvented by clever engineering, do not waste time and resources studying it), there does not exist a sound scientific basis for the understanding and optimization of semiconductor crystal-growth processes and, concomitantly, there is a paucity of support for the necessary research in academia. Although this theme is perhaps somewhat overdone, its substance nevertheless rings true. Dr. Witt then goes on to state, "The academic research volume in crystal growth increased noticeably when NASA decided to focus on basic research deemed necessary for a meaningful exploration of the potential of a reduced-gravity environment. This thrust gained momentum when controversial

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experimental results obtained from experiments in space attracted scientists and engineers from peripheral disciplines."

Buried in these statements is a nugget worth further development, namely, the role of low-gravity crystal growth as catalyst to stimulate the activity of the scientific community to remedy the lacking scientific bases of crystal-growth processes in general. Indeed, the low-gravity environment has presented scientists and technologists with a new mystery factor (or lack thereof, if one prefers to think of the virtual absence of the acceleration, g, due to gravity), the consequences of which have proven to be entirely more subtle than the early space jockeys (perfectly spherical ball bearings, uniform composite materials, and cancer-curing drugs) ever anticipated. Gravity is a relatively weak force when compared with, for example, electromagnetic forces that take part in chemical reactions. However, it can become the deciding factor when such stronger forces either balance one another or are otherwise held in abeyance. For instance, gravity has little effect on the chemical potential of a solute in solution (except for columns of great height or near a critical point). If such a solution should separate into two phases due to the balance of electromagnetic forces, then gravity will affect each phase significantly differently, thus giving rise to all sorts of sedimentation phenomena.

Therefore, in attempting to exploit the low-gravity environment for useful purposes, it is proving to be necessary to advance the science of crystal growth to a much greater depth of understanding, especially by extensive related ground-based research. Hence, in addition to providing important knowledge and technology in its own right, low-gravity crystal growth is also an important catalyst for further research.

The Nature of Convection as Culprit

When Dr. Witt states, "... research efforts aimed at quantifying the growth and segregation behavior in industrial-scale systems have been of limited success only, primarily because of major complications in the heat and mass transfer characteristics caused by gravity-induced convection phenomena," and again "a microgravity environment can, moreover, be expected to provide for crystal-growth conditions under which fundamental complications deriving from gravity induced nonsteady convective flows can be avoided," he dwells on convection as the major phenomenological culprit in inhibiting the degree of perfection of crystals and a firm scientific understanding of their

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growth processes. With all due respect for this important point of view, however, this author would like to point out that there are other nearly equally important factors.

The present author would certainly grant that the very nature of convection (an intrinsically nonlinear phenomenon beset with a hierarchy of instabilities) can lead to an uncontrolled, even chaotic, environment that appears to obscure or even defy a quantitative scientific understanding. In this respect, Dr. Witt is entirely correct and the low-gravity environment provides a setting wherein there may be great simplification or at least the ability to explore the effect of a very different gravitational parameter. But even so, crystal-growth processes employ real materials and processing conditions, and the following factors, which may be of comparable importance, should not be ignored.

- Our knowledge of material constants is painfully meager for most materials. To quantitatively analyze a typical steady state alloy crystal-growth process, even without convection, five dimensionless parameters are needed, which are dependent on a knowledge of some 10 material constants and three processing parameters. Many such material constants are poorly known (especially surface tensions and diffusivities) and it is not particularly glamorous work to measure them. Perhaps they must be measured, perhaps in concert with a long-term commitment in national laboratories or else as an important and recognized by-product of other research.
- Our ability to accurately sense the processing parameters that govern crystal growth processes needs improvement for truly quantitative studies to be meaningful. Although Dr. Witt notes that hardware available for experimentation in space remains limited and deficient, the present author would like to clarify this point. Until recently, the approach has been to employ contractors to produce general-purpose equipment for research in low gravity. Although such contractors have diligently brainstormed the potential user community, the resulting designs have been largely based on a synthesis of existing technology, have not been tailored to the needs of actual experimenters, and have sometimes resulted in hardware with a cost beyond belief and a utility that is inhibiting to the very research that it is intended to enable. What is needed is a new approach to hardware develop-

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ment that is integrated with an innovative approach to new sensors and with the specific needs of a particular principal investigator.

- Our ability to perform complex computational analyses is still an important limiting factor. This need ranges from our present meager understanding of the constitutive laws for transport to raw computational means (supercomputers and the codes to use them effectively) necessary to solve the moving free boundary problems and equations of fluid dynamics and heat and mass transport that underline processes of crystal growth.

A Broader Class of Crystalline Materials and Phenomena

Dr. Witt's chapter is confined, perhaps understandably given his area of expertise, primarily to the growth of semiconductor crystals from the melt, even though many of his remarks apply in a broader context. The present author should like, however, to suggest the nature of a broader context by providing a few examples.

The first example is the growth of crystals from the vapor, as has been carried out in space by Professor H. Wiedemeier of the Rensselaer Polytechnic Institute, among others. Roughly speaking, vapor growth in space, as compared with that on Earth, has resulted in the production of a smaller number of much larger, more nearly perfect crystals of substances such as germanium selenide. The culprit responsible for these differences has been reputed to be convection, but the mechanism seems to involve a very subtle interplay between nucleation and growth and is still being pursued by Wiedemeier and others in ground-based experiments. The point is that researchers must continue to seek to understand the fundamental scientific basis for these results and resist the temptation to rest on their findings and simply employ the space environment for better crystal production. Now that the catalyst to a better fundamental understanding exists, the opportunity to roll back the fundamental frontiers of knowledge of vapor growth processes should become irresistible. Even from a practical viewpoint, the best possible outcome would be to sufficiently understand the process such that the products produced in space can be duplicated by new, more economical processes on Earth. Thus, this example provides a goal, an unexpected target that should further impel researchers to understand and accomplish economically what is now known to be possible.

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The second example is that one of the most dramatic results of crystal growth in space so far has been the ability to grow large crystals of proteins from solution, up to 1000 times the volume of such crystals grown on Earth. Crystals of lysozyme and β-galactosidase (a key enzyme in genetic investigations) were grown aboard Spacelab-1 under the direction of Drs. W. Littke and C. John of the University of Frieburg, F.R.G. and hold the promise of accurate structure determination of proteins by means of powerful and trustworthy techniques of X-ray diffraction. Such knowledge is essential to the development of many aspects of molecular biology as well as to the science of crystal growth itself. Although there are large density differences between the protein solution, the salt solution, and the intermediate buffer solution in which crystallization takes place, and the reduction in low gravity of convection to tolerable levels of laminar flow is of doubtless importance, such proteins typically have molecular weights of 10,000-100,000 and are likely to interact with buoyancy and viscous forces on a microscale heretofore unappreciated by those who think in terms of metallic crystals or crystals composed of small molecules. In other words, researchers still really do not understand in detail the scientific basis for this success. These important results therefore suggest several interesting problems of fundamental as well as profound practical significance.

The Role of NSF

The key question of this workshop concerns the role of NSF regarding opportunities for research in a low-gravity environment. Although Dr. Witt has discussed the desirability of related academic research, his connection to the role of NSF is left more vague; therefore, the present author will attempt to embellish a little.

In the opinion of this author, the role of NSF (and this also possibly applies to other agencies that support basic research in universities) is to act as the precursor, harmonizer, and extender of the fundamental science that is synergistic with the NASA effort in a low-gravity environment. Given the remarks presented above, there are several important Earth-based scientific studies that are both desirable and necessary, before and after the conduct of experiments in space. This is not to say that NSF-sponsored investigators should not conduct experiments aboard spacecraft provided that they stand up to peer review in the broader context of scientific opportunities. Rather, it is simply to say that NASA is, and will

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probably remain, the prime provider and stimulator of the space-based experimental activities, including broader responsibilities toward commercialization. NSF has a much broader scientific mission; however, within this mission there is both opportunity and reason to conduct research that is synergistic with the low-gravity work of NASA.

The primary role of NSF should be, therefore, to respond positively to the opportunities for exciting fundamental science that reinforce or develop from this effort and to give them the ongoing care and attention that they deserve.

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Opportunities for Metals and Alloys Research in a Low-Gravity Environment

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Introduction

With the establishment of regular space shuttle missions and the conclusion of numerous successful in-flight experiments, the field of low-gravity research has developed to the point that experimentation in a low-gravity environment has to be regarded as a potentially viable option when planning many scientific investigations. This chapter defines the perspectives for conducting metals-processing research in a low-gravity environment, identifies potentially promising areas for scientific investigation, and suggests a possible framework for organizing such an effort.

Perspectives

There are three principal reasons why experimentation in a low-gravity environment is appealing in the metals and alloys processing field.

First, if gravitational effects are minimized, buoyancy-driven convective flows also are minimized. It follows that flows due to density differences, brought about either by concentration or temperature gradients, will be reduced or eliminated. Convection can seriously interfere with the measurement of transport coefficients (which requires that gradients be maintained), particularly for double-diffusive phenomena, and can hamper nucleation and undercooling studies and the investigation of a host of other transport-related phenomena.

Second, the presence of gravity will cause sedimentation, the settling and coalescence of nuclei, and possibly phase separation. Such sedimentation may interfere with attempts to produce uniformly dispersed second phases or appropriately aligned second phases in melts.

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Third, operating in low gravity should facilitate containerless processing by suspending specimens in an acoustic or an electromagnetic force field. This mode of operation eliminates contamination, enables the study of difficult-to-contain materials, and prevents the nucleation of new phases at the container surface. The last factor aids in nucleation studies and also in undercooling.

Two important comments ought to be made here. First, experimentation in a low-gravity environment enables the investigator to study key phenomena in the metals and alloys field, which would be very difficult, if not impossible, to pursue under Earth-bound conditions. Second, none of the problem areas defined can be regarded as "pure metallurgy." Indeed they contain significant components of fluid mechanics, transport phenomena, and electrodynamics. It follows that proper definition of the problems and key experiments to address them will require collaboration with the fluids and transport communities.

Key Research Areas in Metals and Alloys

The following are key research areas in the metals and alloys fields that would benefit from experimental work in a low-gravity environment. The list is not exhaustive and no prioritization has been attempted.

Solidification Research

Solidification is of importance in metals and alloys processing because refining and purification are necessarily performed in the molten state, whereas the finished product is in solid form. It is well-established that the structure and properties of alloys depend critically on the growth processes that occur during solidification, which in turn are governed by the nature of the thermal and the solutal fields. In metals solidification, the time scale for heat transfer is some 1,000 to 10,000 times faster than the corresponding values for solute diffusion. Thus, the motion of the solidification front tends to be controlled by heat transfer, but the actual interface morphology and the resulting microstructure are controlled by solute transport. If convection is present during solidification, which is almost always the case, the local balances between heat and mass transfer may be drastically altered, with corresponding changes in the resultant microstructure and properties.

In recent years, major advances have been made in the development of a theoretical understanding of how solidified structures are evolved in the absence of convection. However, convection is virtually impossible to avoid under terrestrial

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conditions; experimentation in a low-gravity environment would provide a unique means for testing these models.

Specific topics that could be addressed here include the following:

- o Morphological stability
- o Columnar-equiaxed transitions
- o Macrosegregation
- o Microsegregation

To comment briefly, the morphological stability of an advancing solidification front determines whether this front will be planar or dendrites will be formed.

In the solidification of metallic structures, one distinguishes between larger, columnar crystals, which have a well-defined orientation (on the outside) and equiaxed crystals (in the interior), which are in essence nonoriented grains.

Segregation phenomena result because the solubility of impurities tends to be less in the solid phase than in the melt, so that impurities (solute) are rejected when the solidification front advances from the solid into the liquid. The subsequent redistribution of these impurities due to liquid motion and other factors are the cause of compositional inhomogeneities in the final solidified structure.

Experimental work involving the controlled solidification of well-defined alloy systems in low gravity and the careful structural analysis of the solid structures obtained should resolve many fundamental problems that are of crucial current interest in this field.

Undercooling-Nucleation-Recalescence Research

Once a solid phase is nucleated in an undercooled melt, the resultant solidification process occurs rapidly. This process may yield interesting structures, moving "frozen" non-equilibrium compositions. By operating in a containerless mode and in the absence of convection, it should be possible to attain a very high degree of undercooling, limited only by the onset of homogeneous nucleation. It follows that by carrying out undercooling-recalescence experiments in a low-gravity environment, hitherto unattainable insight may be obtained into homogeneous nucleation theory and the formation of frozen metastable phases in the bulk. Work of this type has been initiated by Turnbull, and important work is being carried out by Perepezko and Flemings.[1]

Sedimentation, Stability, and Coarsening of Two-Phase Mixtures

In two-phase engineering alloys and in dispersion-strengthened materials it is highly desirable to attain a spa-

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tially uniform, homogeneous dispersion of the two phases. This homogeneity is difficult to attain under Earth conditions because of sedimentation of the heavier particles and because of the diffusion-aided growth (e.g., dendrite coarsening, Ostwald ripening). By carrying out experiments pertaining to the solidification of two-phase systems in a low-gravity environment, it may be possible to eliminate or at least minimize the effect of gravitational settling and the convection-aided components of dendrite coarsening, particle coalescence, and so forth.

Thus, experimentation in a low-gravity environment has two principal attractions: one may produce structures that would have been unattainable in a terrestrial environment and, more important, one may obtain a greatly improved insight into the process mechanisms.

One additional, significant point ought to be made here. Through the preparation of the ideal structures (i.e., uniformly dispersed particles or uniformly aligned fibers), one may devise important standards for both testing the applicability of existing theories and determining materials-processing objectives that ought to be approached within Earth-bound experimental programs.

Measurement of Thermophysical Properties

In recent years, the ability to model metals-processing operations mathematically has advanced greatly through the statement of the appropriate kinetic and transport equations. One major stumbling block in the use of these models, however, is the nonavailability of transport coefficients, such as specific heat, thermal conductivity, diffusivity, contact angle, and surface energies.

Accurate measurement of these parameters is quite difficult in an Earth-bound environment because convection is very hard to eliminate when maintaining materials at elevated temperatures. Furthermore the very transport process that is being studied may interfere with the measurements. Thus, the determination of diffusion coefficients, thermal conductivities, and specific heats, especially of corrosive and difficult-to-contain materials, would represent an important contribution to the field of metals processing.

Contiguous Transport Phenomena

One of the most important attributes of a low-gravity environment for research purposes is that buoyancy-driven convection is eliminated or minimized. For this reason, in the planning and interpretation of in-flight experiments by the metallurgical community, it is crucial that a good quantitative

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understanding be developed of the transport aspects of these problems. These problems need not be tackled by metallurgists alone, but should be carefully considered, perhaps in collaboration with experts in the transport area. Some selected topics in this field are listed below.

Convection at Low Residual Gravity Levels and Gravity-Jitter. In many low-gravity experiments it is impossible to eliminate gravity altogether; indeed reduction of the force of gravity by a factor of 1,000 or 10,000 may be all that can be attained. Furthermore, during spaceship accelerations, time-dependent variations in acceleration forces may occur. The effect of these forces has to be factored into the planning of the experiments. It has been shown that cyclic variations in g, due to either spaceship movement or the movement of astronauts or machinery aboard the spacecraft, may have a marked effect on certain phenomena, such as the distribution or redistribution of impurities in crystal growth.

Surface-Tension-Driven (Marangoni) Flows. It came as an unwelcome surprise to many early investigators in the materials field that, whereas operation in a low-gravity environment minimized buoyancy-driven flows, surface-tension-driven flows were not affected. Indeed, such flows could become dominant, giving rapid enough convection, especially in the presence of free-liquid surfaces, to obviate most of the beneficial effects of the low-gravity environment. In this context, Marangoni-type flows are defined as flows resulting from a surface shear, which in turn may be induced by the existence of temperature or concentration gradients occurring at the free surface of a liquid. Such situations will naturally arise and may indeed be difficult to avoid when a melt having a free surface is being handled (heated, cooled, solidified, etc.) under intrinsically non-isothermal conditions. It follows that quantitative awareness of Marangoni-type flows is essential in the planning of low-gravity experiments.

Electromagnetically driven flows. Because electromagnetic levitation is one of the key methods employed in containerless processing, it is important to assess quantitatively the role played by the residual electromagnetic forces in producing convection and the transient decay rate of such a convection.

Double-Diffusive Flows and Coupled-Flux Phenomena. Many metals-processing operations involve the simultaneous transfer of matter and thermal energy and the coupling of other transport phenomena. Thermal diffusion (e.g., the Soret Effect and the Dufour Effect), electromigration, and the like may be cited as examples. By carrying out experiments in a

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low-gravity environment, the role of convection in modifying these phenomena may be minimized. Such an arrangement may also be ideal for determining the appropriate transport coefficients for these coupled-flux phenomena.

Double-diffusive phenomena is the general term used to describe these systems, whereby two or more transport phenomena (e.g., diffusion and heat transfer, diffusion and electromigration) proceed simultaneously and in a coupled manner. As an example, consider the solidification of a binary system, where convective motion is induced in the melt due to the combined effect of temperature and composition gradients. In such systems, transport of material will occur as a result of diffusion, convection, and thermal diffusion. Therefore, the analysis of the measurements is quite difficult, especially if one seeks information on thermal diffusion (i.e., transport of material due to a temperature gradient), which may be masked by the other phenomena. Another example may be electromigration, the transport of material in an ionic melt due to imposition of an electric field. This phenomenon is opposed by diffusion and could be complicated if thermal natural convection occurs as a result of heat generation.

Discussion

This chapter has identified 1) the principal reasons for conducting metallurgical research in a low-gravity environment and 2) several key research areas that would be particularly appropriate for low-gravity research, namely solidification research, undercooling and nucleation experiments, and the measurement of transport properties. Reference has also been made to the extensive documentation that describes key current efforts in these areas.

Many low-gravity experiments on metals and alloys could be proposed. The following criteria are suggested for selection of those experiments that could qualify for conduct in space. First, an important scientific issue should be addressed by the proposed experiment. Second, the experiment should rely critically on the unique attributes of a low-gravity environment (viz, suppression of convection sedimentation, and so forth). Third, appropriate theoretical and ground-based work should be carried out prior to the in-flight experiment. These have been the guiding criteria in the very successful NASA Microgravity Science and Applications Program to date.

Definition of Metallurgical Research Areas That Meet These Criteria

The areas of metallurgical research defined above have been selected to meet these criteria. More specifically, convec-

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tion is known to have a marked effect on the morphology of solidified structures, on interface stability, and on macrosegregation. Furthermore, the nature of convection in many of these systems is well-enough understood that the effectiveness of research in a low-gravity environment can be adequately assessed. Similar considerations apply to nucleation, undercooling, and sedimentation phenomena. A great deal of excellent fundamental research is being conducted in this field under NASA sponsorship.

Conclusions

There are significant opportunities for fundamental research in a low-gravity environment in the metals and alloys field. Such work would address significant scientific questions and would make use of the unique attributes of a low-gravity environment. This environment would suppress buoyancy-driven flows and sedimentation and thus provide unusually attractive opportunities for studying solidification phenomena, nucleation, and undercooling and for measuring thermophysical coefficients.

A substantial research program is already in place within the framework of the NASA Microgravity Science and Applications Program. This effort is well-documented,[1-5] and there is an ongoing effort to define appropriate research areas. Fluids and transport phenomena, metals and alloys, and crystal growth are specific scientific disciplines that are being examined under the NASA program.

References

[1]The "Goals Documents" of the Metallurgy DWG (Chairman, M. Glicksman) Fluids and Transport Phenomena DWG (Chairman, J. Szekely) of NASA's Microgravity Science and Applications Program.

[2]Pentecost, E., "Microgravity Science Applications Bibliography," NASA TM-86651, September 1984.

[3]Dodge, F.T., Abramson, H.N., Angrist, S.W., "Fluid Physics, Thermodynamics, and Heat Transfer Experiments in Space," NASA CR-134742, January 1975.

[4]Pentecost, E., "Microgravity Science and Applications Program Tasks," NASA TM-87568, May 1985.

[5]Guyenne, T.D., Proceedings of the Fifth European Symposium on Materials Science Under Microgravity, The European Space Agency, 1985.

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Comments on Metals and Alloys

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After learning about the experiments on Skylab, Deere and Company began to discuss the possibilities of low-gravity research on a material of importance to our company. Cast irons were chosen because they represent 25% by weight in Deere's products and because they are the one material that the company processes in a liquid-to-solid transformation. After some discussion, Deere decided to concentrate on the phenomena of microstructure development during solidification because the microstructure, and particularly the graphite, is so significant in the castability of the iron, the machining of the castings, and the properties of the finished component. It was believed that a more thorough understanding of the formation of the microstructure would aid Deere in developing improved irons or improved processes in its foundries. At no time did the company imagine that it would be possible economically to manufacture castings in space.

From this concept, Deere developed a Technical Exchange Agreement with NASA, conducted experiments in its own laboratory to develop the furnace and the instrumentation for data collection, and performed models of solidification of the NASA sample to predict the time and progress of the cooling during solidification. The company then conducted experiments on several cast irons onboard KC-135 and F-104 aircraft. These aircraft developed periods of low gravity for about 20 s on the KC-135 and 52 s on the F-104. The short periods of solidification in low gravity revealed structural differences in these cast irons from those solidified on Earth. However, the period of low gravity was too short for any quantitative studies. Therefore, Deere is now preparing a Joint Endeavor Agreement with NASA to conduct tests of longer duration onboard the space shuttle.

Dr. Szekely notes in his chapter that there are three principal reasons for experimentation in a low-gravity

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environment. Of these three, two represent Deere's reasons for wanting to conduct experiments in the space environment, namely, the reduction of buoyancy-driven convection to a minimum and the near elimination of sedimentation in the low-gravity environment. Although Deere acknowledges the benefit stated in the third reason (i.e., containerless processing is possible), it is not relevant to its experiments on cast irons.

Dr. Szekely also mentions several research areas. In discussing the first of these, solidification, he properly notes that the structure and properties of metal alloys depend very critically on the growth processes that occur during solidification. This is indeed the subject of Deere's research on cast irons and why the company believes that it is worth doing to gain a better understanding of this phenomena so that it can improve its processes and cast irons made on Earth. After a review of its early experiments, Deere established several possible subjects for future exploration (Table 1).

Deere plans in its future tests to use a directional solidification furnace whereby the rate of heating and cooling can be changed substantially. The company plans to vary the rate of traverse to a 300-mm sample from 10 min to 11 h. This will enable Deere to study the various subjects mentioned in Dr. Szekely's chapter, such as undercooling, nucleation recalescence, sedimentation, and transport phenomena. These subjects will be included in the company's future low-gravity tests on cast irons.

Deere has been developing computer models for predicting the cooling curves of castings in the foundry. These models are needed to be able to better design the patterns, gating, and risering to arrive at uniform rates of

Table 1 Subjects for low-gravity tests on cast irons

Process Management
Carbon flotation
High carbon iron phase diagram
Cell size control
Diffusion measurement liquid-solid
Quantify difference caused by lack of convection
Design Data
True liquid thermal conductivity
Properties of high carbon
New Materials

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cooling throughout the casting. This will reduce the residual stresses that are detrimental to the castings and sometimes cause extra processes to eliminate. In developing these models, Deere finds it necessary to use values for various parameters to make these predictions viable. These include thermal conductivity, diffusivity, contact angles, surface energies, specific heats, and others. This author was pleased to see that these were mentioned in Dr. Szekely's chapter. The development of good data on these factors is very important to the advancement of the metals industry; quite often, information of this type and quality is unavailable. The Numerical Data Advisory Board of the National Research Council has also noted this point.

After Deere began its tests onboard the aircraft, the company found a University of Alabama professor who was extremely interested in foundry processes and Deere's research in a low-gravity environment. This individual's observations and knowledge of cast iron and theories of diffusion, nucleation, and dendrite growth have been invaluable in Deere's planning of future research. This began a union of national laboratories, academia, and industry whereby each of the groups has a mission and special interest that also requires the input of the other groups. NASA has the facilities to conduct the experiments in space, the university has the mission of fundamental research, and industry has the desire to commercialize the understanding gained.

NASA has already performed some primer experiments and materials research in space. They have excellent facilities for conducting research in low gravity, such as drop towers, aircraft, and the space shuttle; furthermore, they are in the process of planning the space platform for the future. This distribution of facilities makes it possible for an organization to begin research in a modest way and determine whether it is worthwhile proceeding to the shuttle or to the space platform. As for Deere's experience, the company performed tests in its own laboratory and then proceeded to test in aircraft. These tests revealed enough of benefit that Deere is now in the process of planning testing onboard the space shuttle. At this time, the company does not see the need for using the space platform in its experiments on cast iron. However, the more that is learned, the more Deere imagines and thus will not rule out the potential of conducting some type of future experiment on the space platform.

The present author would also like to discuss the need for a multidisciplinary approach to low-gravity research. Dr. Szekely's chapter points out many research situations that would benefit from the input of several

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disciplines. Indeed, the coordinated efforts of several disciplines' research in a space environment will be more effective than the individual efforts of each discipline.[1] Even on Earth, the multidisciplinary approach has proven to be extremely valuable. An illustrative example from Deere points out the diversity of input needed in its foundry processes. In its research to develop and improve metal-casting technology (i.e., the lost foam molding process), the company is applying the expertise of scientists from the following fields: foundry processes, chemistry, computer modeling, metallurgy and mechanical properties. As Deere experimented with lost foam molding, it became necessary to bring in the following outside technologies:

- Fracture control from the University of Illinois
- Concepts on the influence of convection from low-gravity tests with NASA
- Thermal reactions of polymers and computer models from NASA and the National Bureau of Standards
- New organic materials from a research institute
- Computer-controlled vibrators from another company
- Advanced core wash from a chemical supplier
- Polymer technology from a plastic company

Deere encourages NSF to consider the benefits of a multidisciplinary approach in future research in a low-gravity environment.

Japan, the Soviet Union, and many European nations are making determined efforts to conduct research on metals in low-gravity environments. The collaborative efforts of industry, government, and academia in each of these nations have resulted in extensive studies of the potential for research on materials in a low-gravity environment and specific research plans. Similarly, the United States should build on NASA's research to extend our knowledge of metals and alloys. The benefits of such efforts are twofold: 1) opportunities can be realized for the effective processing of these materials in a space environment and 2) experience from research conducted in a low-gravity environment will help in future terrestrial processing of these materials.

If the United States does not proceed in a synergistic union of government, academia, and industry, it will not remain the leader in low-gravity research. NSF can aid in advancing our scientific knowledge, which will benefit the nation through the development of new or better commercial products and enhance our nation's economic com-

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petitive position in the world marketplace. Support of this research at the universities will further expand their capability to supply well-trained scientists and engineers to support U.S. industry.

Reference

[1]Panel on Engineering Research Centers, National Academy of Engineering, Guidelines for Engineering Research Centers, National Academy of Engineering, Washington, DC, 1984, p. 1.

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Research on Containerless Melts in Space

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Introduction

Facilities provided by NASA have created new opportunities to use space for scientific study and applied research. From the standpoint of materials, one of the most unique and important advantages of space is an environment of reduced gravity, typically 10^{-4} to 10^{-6} g. Low gravity has little effect on solids, but fluids are affected in several important ways, namely the reduction of hydrostatic pressure, buoyant forces, natural convection, and sedimentation or segregation. Many materials, such as steels, alloys, glasses, and some refractories, are prepared from fluids and, therefore, are sensitive to gravity-driven processes. The opportunity to eliminate or minimize the often undesirable effect of gravity in fluids may help to achieve control over the microstructure, properties, and performance of many materials. It is not surprising, therefore, that materials scientists are being attracted to the unique laboratory of space for investigating materials. The possibility of achieving uniformly dispersed, multiphase materials in low gravity is an important driving force for developing new composites that might never be prepared on Earth because of segregation due to gravity.

Several basic phenomena arising from forces that are relatively weak, compared with those due to gravity, cannot be easily studied on Earth. Surface effects and interfacial phenomena, concentration gradients in the absence of convection, the effect of cohesive or adhesive forces, diffusive transport in low-viscosity liquids, and the chemical corrosion of a solid by a melt are a few topics that could be investigated more effectively in low gravity.

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The near weightlessness of a solid or liquid in low gravity makes it unnecessary to support or hold the material in a container. This unique advantage of low gravity has generated new concepts about materials processing. Containerless melting or heat treating avoids undesirable effects such as chemical contamination or heterogeneous nucleation from the container. Thus, ultrapure materials can be produced. Highly corrosive melts, for which a nonreactive container may not exist, can be processed in low gravity without serious difficulty and remain uncontaminated.

The list of scientific investigations that can benefit from low gravity is becoming increasingly large. Described below are some of the apparatus being developed for containerless processing in space, and an overview of research opportunities on containerless melts in space is given.

Containerless Processing

Zero gravity can, in principle, be achieved in any noninertial frame in which the d'Alembert forces balance the gravitational force due to Earth's acceleration. A truly zero-gravity environment can never be achieved in an orbiting spacecraft, so the terms "low gravity" or "microgravity" are commonly used. Accelerations associated with spacecraft trajectory, atmospheric drag, and crew movement lead to motions relative to the spacecraft's center of mass.[1] As a result, a residual gravitational acceleration, whose magnitude and direction change with spacecraft position and time, acts on any mass in the noninertial frame. Depending on the nature of the residual gravity vector, the elementary mass drifts in an irregular way. To accurately perform containerless processing, the experimental sample needs to be held in a fixed position by an externally generated force, the intensity of which depends on the gravity level of the spacecraft. Before discussing the different means of sample positioning, the containerless-processing facilities currently available are discussed briefly.

Containerless Processing Facilities

NASA has developed several facilities in which low gravity can be achieved for different time periods. These include drop towers on Earth, specially designed aircraft and rockets, and the space shuttle. The level and duration of gravity attained in these facilities are summarized in Table 1. Depending on the nature of the experiment,

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one or more of these facilities can be used for low-gravity research.

Drop Tower. A drop tower is a convenient device for performing, on Earth, low-gravity experiments of short duration. It essentially consists of a long steel tube of relatively small diameter. A sample released at the top of the tube experiences a free-fall condition (zero-gravity simulation) for a few seconds. Several drop towers of 14 m to 100 m in length and about 10-cm diam are now in operation,[1,2] in which a free-fall time up to a maximum of 5 s is obtained.

Aircraft. KC-135 and F-104 aircraft frequently are used for low-gravity research. Low gravity is achieved by flying a prescribed parabolic trajectory. In a single trajectory, the gravity level attained in a KC-135 is 10^{-2}-10^{-3} g for nearly 25 s and 10^{-1} to 3 x 10^{-2} g for nearly 60 s in an F-104. The cumulative time at reduced gravity can be increased, though intermittently, by repeating the trajectory several times in a single flight. In the KC-135, technicians can perform real-time experiments, but in the F-104, with only a pilot on board, the experiments need to be fully automated.

Rockets. NASA's Space Processing Applications Rocket (SPAR) Program, started in 1975, provides gravity levels as low as 10^{-5} g for periods of 5-7 min. Black Brant VC sounding rockets, launched from White Sands Missile Range in New Mexico, were used in the program. Experiments were fully automated and designed to withstand both harsh launch and recovery environments. The opportunity provided by this program was used by scien-

Table 1 Duration and gravity level attained in different facilities

Facility	Gravity level (g)	Duration reduced gravity
Drop tower	$\approx 10^{-8}$ (simulation only)	2-5 s
Aircraft	10^{-2} - 10^{-3}	30-60 s
Rocket	$\approx 10^{-5}$	5-7 min
Space shuttle	$\approx 10^{-6}$	Typically 10 days

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tists conducting research under low-gravity conditions on more than 40 experiments. Many experiments dealing with materials were conducted in the nine SPAR flights.

Space Shuttle. A truly low-gravity environment ($<10^{-6}$ g) can be achieved for more than 10 days in the space shuttle, and experiments requiring low gravity for longer periods of time will be possible on planned "free flyer" platforms. The relatively smooth launching and landing of the space shuttle makes it attractive to scientists using sophisticated and sensitive experiments. Many experiments ranging from medical to military science have been successfully completed in space shuttle flights.

Sample Positioning (Levitation) Technique

Containerless processing in low gravity requires some means of controlling the position of a sample to prevent it from drifting into contact with a foreign surface. For a residual gravitational vector of 10^{-4} g in an orbiting spacecraft, the terminal drift velocity of a particle after 60 s will be about 6 cm/s, and it will have drifted 176 cm. The drift velocity and drift distance at 10^{-6} g will be 0.06 cm/s and 1.8 cm, respectively. This drift usually is objectionable, as, for example, when it is necessary to position a sample at the maximum temperature zone inside a furnace. For gravity levels between 10^{-4} to 10^{-6}, sample positioning can be achieved with relatively small forces that reduce unwanted side effects such as inhomogeneous heating, vibrations, convection, and deformation. Methods using forces from electrostatic,[3] electromagnetic,[4] or acoustic fields,[5-7] from high-velocity gases flowing through a constricted tube[8,9] or from gas jets have been used to position or levitate a sample. Each method has specific advantages, and no single method appears satisfactory for all types of liquids (from metals to nonmetals). Prototypes are being developed, but a reliable and fully operational apparatus for levitating melts at temperatures above 1,500°C is not available at present. The different types of levitating devices being developed are described briefly below and compared in Table 2.

Aerodynamic Levitation. There are two methods of aerodynamic levitation. In one, the sample is levitated by using a gas flowing at high speed through a constricted tube. The levitation force results from the decrease in momentum of the gas as it passes around the sample. It is difficult to obtain stable positioning using this method, particularly for low-viscosity liquids, and feedback control

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is required. This technique is potentially useful for containerless experiments on Earth, but is not being actively considered for space experiments at present. A second aerodynamic technique uses air jets to support a spherical sample much as a Ping-Pong ball is supported on a flowing gas stream.

Electromagnetic Levitation. In this method, the sample is placed in an alternating electromagnetic field. The force generated by the interaction of the magnetic field with eddy currents induced in the sample holds the sample in the desired position. The sample also is heated by the eddy currents. For a specific sample, a balance between the heating power and the levitation force is achieved by adjusting the shape of the electromagnetic coil and the power and frequency of the electromagnetic field. This technique has the advantage that it can be used in a

Table 2 Advantages and disadvantages of different levitation techniques

Levitation technique	Advantages	Disadvantages
Aerodynamic	Easy to fabricate Suitable for any type of material	Stable levitation is difficult to achieve Feedback control required No vacuum
Electromagnetic	Can operate in vacuum thereby avoiding contamination from a gaseous atmosphere Stable positioning is possible	Only suitable for electrical conductors Generates unavoidable heating and convection in the melt
Electrostatic	Can operate in vacuum	Stable positioning difficult, feedback control required Levitation increasingly difficult for materials with low polarizability
Acoustic	Stable positioning is possible Very weak thermal and mechanical disturbances Suitable for any type of material	Requires a gaseous atmosphere--no vacuum

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vacuum, thereby avoiding contamination of the sample by the surrounding atmosphere. An important limitation for electromagnetic levitation is that the material must be a fairly good electrical conductor. For levitation in space, a minimum conductivity of 10 $(ohm \cdot cm)^{-1}$ is required. An electromagnetic levitator is being developed by NASA for use on the space shuttle.

Electrostatic Levitation. An electrostatic field generated between two or more electrodes can be used to levitate a nonconducting dielectric material. Like electromagnetic levitation, it can be used in a vacuum, thereby eliminating the possibility of contamination from the surrounding atmosphere. Because a static electric field cannot provide stable positioning, feedback control to monitor and correct the position of the sample is necessary.

Acoustic Levitation. In the acoustic method, a sample is levitated at the potential energy minimum (low-pressure nodal regions) of a sound field confined between a sound source and a reflector (Fig. 1). The diameter of the reflector rod should be about one wavelength (λ) of the

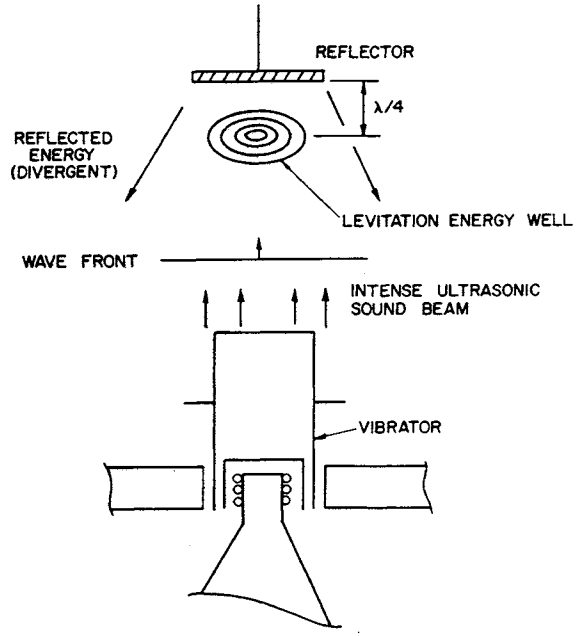

Fig. 1 Schematic of single-axis acoustic levitator showing location of energy well.

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sound used for levitation. A standing sound wave is established between the sound source and the reflector, and a potential energy well is created at a distance slightly greater than $\lambda/4$ from the reflector end (typically 1-3 cm). Other small energy wells also may exist below this primary well; however, by selecting a proper design, in the same way as controlling reverberations in an auditorium, these secondary wells may be made small enough so as to not interfere with the primary well. To obtain a single, well-defined potential energy well, primary consideration must be given to the sound absorption of the furnace atmosphere at the operating temperature, furnace cavity size and acoustic path length, and the nature and shape of the reflecting surface.

The axial force distribution through an energy well of an acoustic levitator operated at 1 g and 1600°C is plotted in Fig. 2 for a specimen 1 cm in diameter. Integration of the curve in Fig. 2 leads to the characteristic potential energy distribution shown in Fig. 3. Objects are levitated in the trough of the potential energy well. The corresponding potential energy distribution along the radial direction is shown in Fig. 4, which is similar but broader than that in Fig. 3. Also, the depth of the potential energy minimum is smaller in the radial direction than that in the axial direction. The probability of a specimen escaping from the potential energy well, therefore, is higher for the radial direction.

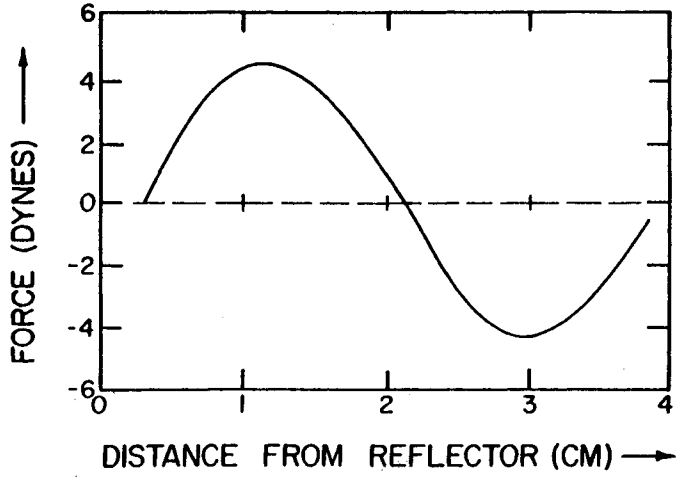

Fig. 2 Force distribution through the energy well of a single-axis acoustic levitator.

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The advantage of acoustic levitation is that any material, conductor, or insulator, magnetic or nonmagnetic, whose density is considerably higher than that of the surrounding gas, can be levitated. Sample dimensions are limited (usually 1-2 cm), however, because the sample should be significantly smaller than the sound wavelength used for levitation to achieve stable positioning. All experiments also must be conducted in a gaseous atmosphere, which is required for the propagation of the sound wave.

The acoustic levitator just described consists of a single sound source and a reflector and is known as a

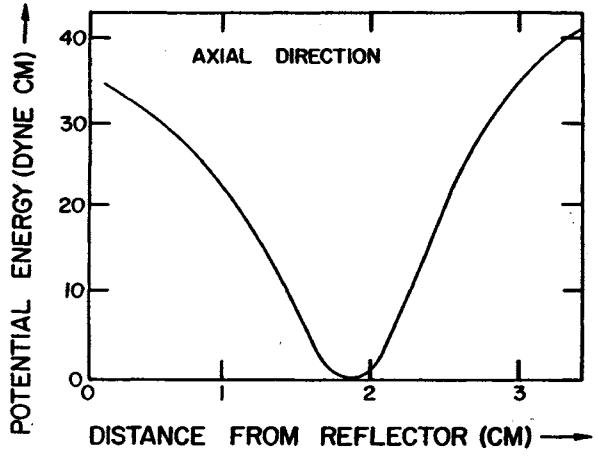

Fig. 3 Potential energy distribution through an acoustic energy well in the axial direction, single-axis levitator.

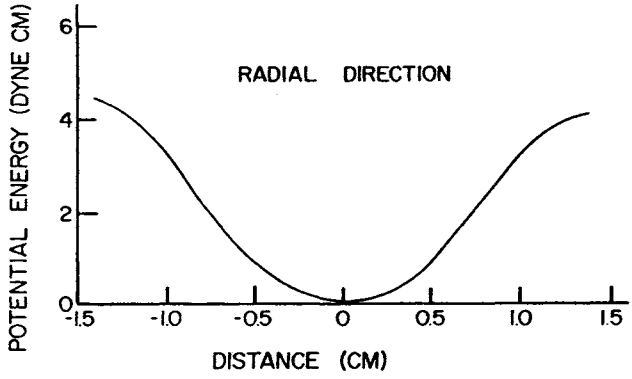

Fig. 4 Potential energy distribution through an acoustic energy well in the radial direction, single-axis levitator.

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single-axis levitator. Described in Ref. 10 is the latest version of a single-axis levitator/furnace capable of processing materials up to 1600°C and developed for NASA by Intersonics, Inc., Northbrook, Illinois. Typical operational data of the levitator/furnace is given in Table 3.

A triple-axis acoustic levitator[1,11] that uses three sound sources and reflectors in mutually orthogonal directions also is being developed for containerless research in space. In a single-axis levitator, the specimen is constrained to move in a plane perpendicular to the line joining the driver and the reflector. In a triple-axis system, when all three drivers are excited, the specimen is located at a point, which is the intersection of three axes (Fig. 5). This allows stable positioning of the sample and makes it possible to rotate or spin the sample about any desired axis. A contactless specimen translation from one part of the furnace to the other also is possible. By controlling and adjusting the acoustic forces in any of the techniques (single- or triple-axis), liquid samples can be deformed to simple shapes. The temperature capability of the triple-axis levitator is not very high (≈600°C) presently, and work is now under way to increase its temperature range.

Single- and triple-axis levitators have been used in several containerless experiments. Their capabilities have

Table 3 Operational parameters for single-axis acoustic levitator/furnace

Parameter	Measure
Temperature_{max}	1600°C
$\text{Heating rate}_{max}$	2°C/s above 800°C
Cooling rate	variable and controlled, $30°C/s_{max}$
Power requirement	2800 W
Frequency of sound source	15 kHz
Continuous operation time_{max}	1 h
Sample insertion time	1 s
Specimen size	6 ± 1 mm
$\text{Number of samples}_{max}$	8

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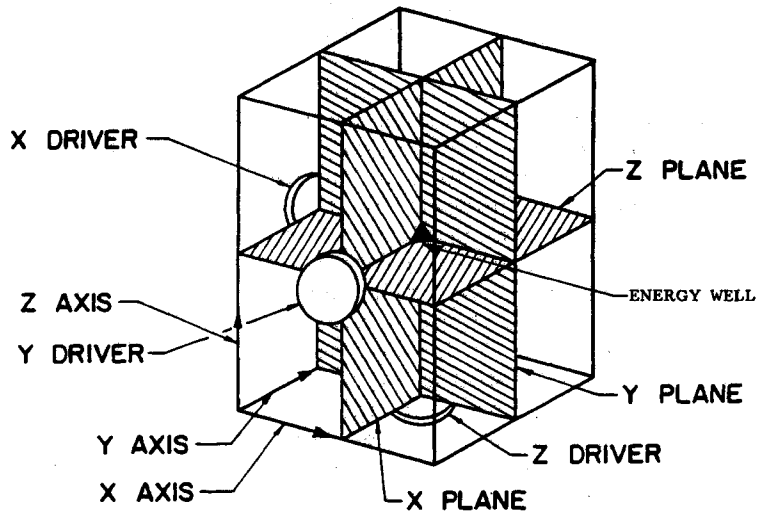

Fig. 5 Three-axis acoustic levitator; energy well is at intersection of X, Y, and Z planes.

been verified at low gravity in KC-135 airplanes and in several rocket flights (SPAR 4-8). The single- and triple-axis levitator/furnaces have been used for containerless experiments on glass-forming systems on recent space shuttle flights, and the results are encouraging.

Research Opportunities for Containerless Melts

Containerless processing in space offers new opportunities in two broad respects: 1) for conducting research on properties and phenomena that, on Earth, are seriously affected by such things as gravity-driven convection, contamination from a container, and sedimentation; and 2) for the unique processing of materials. These materials, processed in an unsupported manner, may have unique properties and could find use in special engineering and technological applications. As mentioned earlier, there are many research areas that could benefit from low gravity. In addition to low gravity, many experiments might be best performed without a container. These experimental areas are summarized in Table 4 and are discussed in the following sections.

Scientific Studies of Properties/Phenomena

High-Temperature Property Measurement. Reliable data on thermophysical properties at high temperature

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Table 4 Research opportunities for containerless melts

Scientific studies of properties/phenomena
o High-temperature property measurements
o Nucleation, crystallization, and glass formation
o Immiscible liquids
o Transport processes/melt homogenization
o Studies and control of weak forces
o Surface studies
Processing of materials for engineering/technological applications
o Ultrapure materials
o Composites of unique microstructures
o New metallic/nonmetallic glasses
o High-temperature treatment
o Unique shaping
o Crystal growth

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(above 1600°C) are not available for many materials, especially for those that are highly corrosive or refractory and for which there is no suitable container material. The containerless technique provides an uncontaminated and unsupported sample at any desired high temperature so that its properties can be determined, provided suitable noncontact means of measuring these properties are available. Several methods[12-14] of determining the thermophysical properties of unsupported samples at elevated temperatures have been developed. For example, heat capacity and thermal diffusivity can be determined from the rate of cooling for a known amount of sample.[15] Surface tension and viscosity can be calculated by setting a liquid sphere into oscillation and measuring its period and damping rate.[16] The emissivity can be determined by measuring the power input to a sample and the radiation output.[17] One serious limitation of the high-temperature property measurement is that a specimen at high temperatures for an extended period of time can undergo, for example, chemical reactions, heat dissipation, and evaporation, which interfere with an accurate determination of the properties. A dynamic technique for measuring the properties at high temperature in a short period of time (less than 1 s) has been developed at the National Bureau of Standards.[18] It is claimed that this technique can be used in low gravity to measure properties such as heat capacity, electrical resistivity, hemispherical total emittance, normal spectral emittance, thermal expansion, melting temperature, heat of fusion, temperature and energy of solid-

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solid phase transformations, and properties associated with time-dependent relaxation processes.

Nucleation/Crystallization and Glass Formation. One of the major advantages of containerless processing is the elimination of container-induced impurities and surfaces that act as nucleation sites (heterogeneous nucleation) for crystallization. In homogeneous nucleation, random compositional fluctuations in the liquid initiate the formation of small structural groups resembling those in crystals. The net free-energy change, W, on forming these nuclei (or embryos) is given by[19]

$$W = -4/3\ \pi r^3\ \Delta G/V_m + 4\pi r^2\sigma \qquad (1)$$

where ΔG is the increase in free energy per mole on forming a spherical nucleus of radius r, σ is the interfacial energy between the crystal nucleus and the surrounding liquid, and V_m is the molar volume.

The variation of W with r in Fig. 6 shows that embryos of radius lower than some critical values r^* are

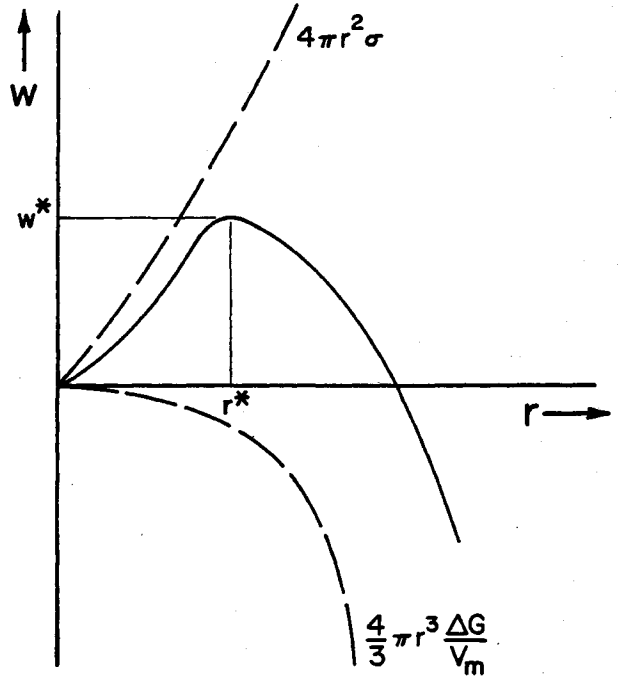

Fig. 6 Energy to form a spherical nucleus (W) as a function of nucleus radius (r).

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thermodynamically unstable, but they become stable and act as potential sites for crystallization when they are larger than r^*. Gravity-driven convection and segregation may increase the frequency of local fluctuations and hence the probability of forming nuclei of critical size. This may also cause a net increase in homogeneous nucleation.

Glass formation, when considered as a kinetic phenomenon, is the opposite of crystallization. The net volume fraction, V_c, of crystals in a melt depends on 1) the overall nucleation (homogeneous and heterogeneous) frequency, I, and the crystal growth rate, u, which both are functions of temperature, T; and 2) time, t, as[20-23]

$$V_c = \pi/3\ I(T)u^3(T)t^4 \qquad (2)$$

If the melt is cooled at a sufficiently high rate so that it is devoid of any detectable crystallization, the product is called "glass" ($V_c < 10^{-6}$). Depending on the characteristics of any particular system, there exists a minimum cooling rate for which the level of crystallization is just detectable ($V_c \leq 10^{-6}$). This is known as the critical cooling rate, R_c. I and u vary with temperature and exhibit a maximum where the increasing thermodynamic force for crystallization on undercooling is counteracted by the increasing viscosity of the melt. The combined effect of I and u results in a nose-shaped curve (Fig. 7) on a temperature-time plot,[24] where T_n is called the nose temperature and the corresponding time, t_n, is the nose time. An approximate critical cooling rate, R_c, derived from this curve is

$$R_c \approx dT/dt \approx \Delta T/t_n \qquad (3)$$

where $\Delta T = T_L - T_n$ (T_L is the liquidus temperature).

If container-induced heterogeneous nucleation is completely suppressed in low gravity, then crystallization is determined by the inner curve of Fig. 7, which results from homogeneous nucleation. Consequently, R_c for glass formation will be lower, and the glass-forming ability of the material is increased. A further reduction in R_c also is expected if the T-versus-time curve for homogeneous nucleation (Fig. 7) is displaced away from the temperature axis due to a lower probability of forming critical-size nuclei in low gravity. Limited evidence of this possibility is provided by a recent experiment in low gravity on germanium-antimony-sulfur glasses. It has been reported[25] that glasses made in low gravity were more resistant to bulk crystallization than identical samples

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melted on Earth because of the smaller number of nuclei they contained.

In experiments on Earth, heterogeneous nucleation/crystallization usually predominates, and it is difficult to study homogeneous nucleation in a totally independent fashion. Heterogeneous nucleation at container surfaces should be eliminated in containerless experiments in space, so it should be possible to study homogeneous nucleation processes in high-temperature melts more thoroughly.

Another direct consequence of the absence of heterogeneous nucleation is that a higher degree of undercooling can be achieved in a melt. Evidence for this has been reported[2,26,27] for niobium-germanium alloys, where an undercooling exceeding 500-700°C below the normal freezing point has been observed. With such deep undercooling, solidification can occur so rapidly that metastable phases can form and produce unique microstructures. This deep undercooling, which is obtainable in low gravity, provides an opportunity to produce metastable phases that cannot be obtained from equilibrium solidification.

Immiscible Liquids. Many multicomponent molten systems form immiscible liquids, that is, a compositional field where more than one liquid of different compositions can exist in equilibrium. This type of microphase demixing becomes possible when the free energy of the system is lowered by separation into two phases. The free energy,

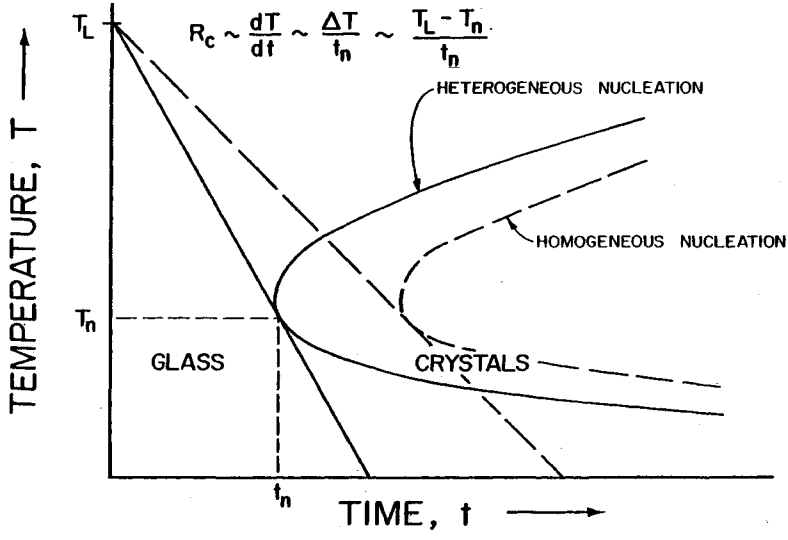

Fig. 7 Typical time-temperature-transformation curve for a material.

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ΔG, for mixing at a temperature, T, can be expressed as

$$\Delta G = \Delta H - T\Delta S \quad (4)$$

where ΔH and ΔS are, respectively, the heat and entropy of mixing and both are functions of composition. When ΔH has a negative or small positive value, the general type of free-energy curve shown in Fig. 8 is obtained, which is characteristic of two miscible liquids.

If ΔH exceeds $T\Delta S$, the free-energy curve contains maximum and minimum as shown in Fig. 9. Any composition

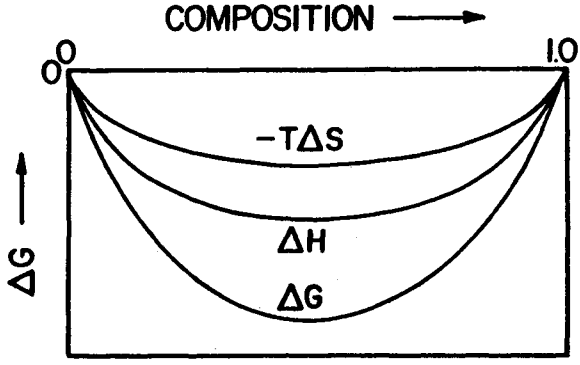

Fig. 8 Plot of free energy versus composition for a melt when ΔH is negative (miscible system).

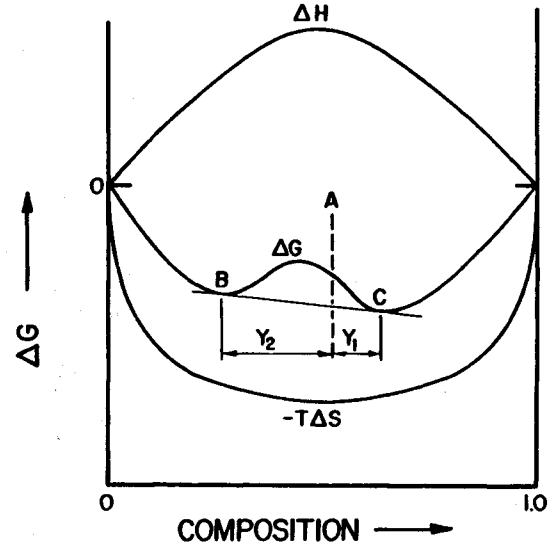

Fig. 9 Plot of free energy versus composition for a melt when ΔH is positive (immiscible system).

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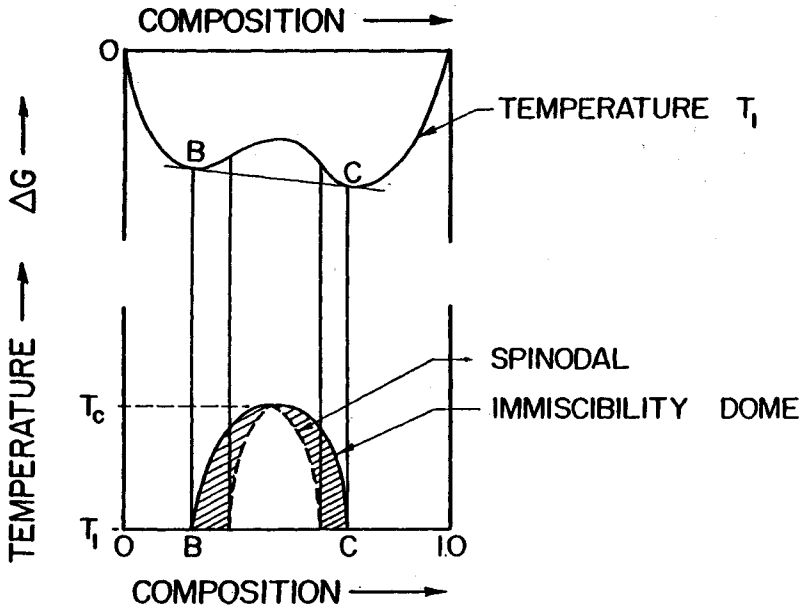

Fig. 10 Relation between free-energy diagram, immiscible region, and spinodal decomposition.

A between B and C in this system will not be stable and eventually will separate into two phases corresponding to compositions B and C where the free energy of the system is a minimum. The relative concentration of the two phases is determined by the usual lever-rule principle. The solubility of one liquid into another usually increases with increasing temperature (by increasing the magnitude of $T\Delta S$ in Eq. [4]), where the magnitude of inflection in the free-energy curve decreases. At a certain critical temperature, T_c, known as consolute temperature, the inflection completely disappears and the two liquids become completely miscible.

Phase separation within the immiscibility region takes place primarily by two processes: 1) nucleation and growth (NG), which has been discussed above; and 2) spinodal decomposition. A temperature-versus-composition curve for systems lying within the immiscibility range has a shape like that shown in Fig. 10, known as the immiscibility dome. The inner curve results from the locus of inflection points in the ΔG-versus-temperature curve and is known as the spinodal. Melts within the hatched area, that is, between the immiscibility dome and spinodal boundary, separate into two phases by the process of nucleation and growth. Those within the spinodal boundary

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separate spontaneously (spinodal decomposition) into two phases without a nucleation step. The morphology of the second phase separated by the NG process is usually spherical with very little connectivity, whereas those separated by spinodal decomposition are nonspherical with high connectivity. Phase separation by the NG process requires a local compositional/structural fluctuation to form a nucleus of critical size that is accelerated by, for example, convection and segregation. Phase separation by spinodal decomposition requires diffusion only.

In low-viscosity liquids such as alkaline earth borates and metals, it is difficult to study the mechanism and kinetics of phase separation on Earth, because the two liquids have different densities and readily separate into light and heavy liquids. In space, where density-driven motion is greatly suppressed, the mechanism of phase separation in liquids can be studied without interference from gravity-driven convection. Studies in space can provide valuable scientific information and potentially produce composite materials with interesting microstructures.

Transport Processes/Melt Homogenization. Mass or heat transport in a melt is governed mainly by two processes: convection, which is a bulk process, and diffusion, which is basically a microscopic process that produces an observable macroscopic effect. Convection in a melt results primarily from two forces: a gravity-driven buoyant force due to density differences, and a force associated with surface tension. If a temperature gradient is created within a liquid bounded by a free surface, a gradient in surface tension is established. This gradient creates flow in the liquid because regions where the surface tension is high move to a higher temperature where the surface tension is lower. This movement produces a convection current in the melt that is known as Marangoni flow or thermocapillary convection. Surface-tension-driven flow was demonstrated by Young et al.,[28] who applied a temperature gradient in the downward direction, to prevent bubbles from rising due to buoyancy.

The relative effect of gravity-induced and surface-tension-induced convection is given by two dimensionless numbers; namely, the Grashof number (G_r) and the Marangoni number (M_a), which are expressed as

$$G_r = \beta g L^3 \rho^2 \Delta T/\mu^2 \tag{5}$$

and

$$M_a = (d\sigma/dT) L \Delta T/\mu k \tag{6}$$

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where σ is surface tension, ρ is density, μ is viscosity, k is thermal diffusivity, β is the coefficient of thermal expansion of the liquid, L is the dimension of the sample, ΔT is the temperature difference, and g is the acceleration due to gravity.

On Earth, the large value for g causes, in most instances, the Grashof number to be much higher than the Marangoni number so gravity-driven convection usually predominates over Marangoni flow. In low gravity, however, G_r can become negligibly small compared to M_a, and surface-tension-driven flow can become as large as buoyancy-driven flow at 1 g, provided a temperature gradient exists within the melt.

On Earth, the contributions of different transport processes are difficult to separate, so the combined effect of several different processes usually is observed. In low gravity, transport due to convection arising from both buoyancy and Marangoni flow can be suppressed, as has been demonstrated experimentally.[29,30] The contribution of diffusion-controlled transport therefore can be studied independently, and more accurate information about the microscopic nature of the material can be obtained. In a recent experiment,[29] the corrosion of vitreous silica by a sodium silicate melt was investigated in low gravity, and the results were compared with measurements conducted under identical conditions on Earth. The system in space showed undisturbed and longer diffusion profiles and higher interdiffusion coefficients.

One potential disadvantage of low gravity is the problem of melt homogenization and fining (removal of gas bubbles), which usually takes place on Earth by buoyancy- and gravity-driven convection. Work is under way to develop a levitation system that will be able to rotate, spin, and shape a molten specimen, but present capability is far from satisfactory. Conceptually, Marangoni flow, created by a temperature gradient, could be used to remove bubbles from a melt in low gravity. Bubbles in a melt can be made to move to a localized hot spot where they can coalesce and where lower interfacial energy should cause them to be destroyed. The feasibility of producing bubble motion and coalescence by surface-tension-driven flow is being investigated[31,32] as a process of fining melts in low gravity.

Surface Properties. The equilibrium bonding arrangement of the ions or atoms situated in the bulk of a material does not exist for ions at the surface. Ions or atoms at the surface (e.g., for a solid in contact with liquid or gas) always have a lower coordination number than do similar

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ions in the bulk. As a consequence, the structure, composition, and, hence, all the properties (e.g., physical, chemical, thermal, optical) of a surface are significantly different from those of the bulk.

A major difference between the structure of the surface layer and that of the bulk is that the surface ions have a greater anharmonicity (and hence a higher entropy) of thermal vibrations. The increase in vibrational entropy lowers the free energy of the system favoring the spontaneous formation of surface regions. This also enhances material transport processes across the surface and makes the surface more reactive than the bulk. As a particular example, it is well-known that molten glass and metals do not react uniformly with refractory containers, but are most corrosive at the melt-refractory-air interface.

In containerless melts in low gravity, it should be possible to investigate an uncontaminated (pristine) and unsupported surface. Many properties and phenomena, such as strength, stability or durability, surface flow, surface nucleation and crystallization, ion-exchange reaction, surface-surface interaction, and rate of gas evolution or vaporization, can be studied to gain a better understanding of the physical, chemical, and structural characteristics of surfaces.

Study and Control of Weak Forces. The forces acting on a material in low gravity are not different from those on Earth, but many of these forces are insignificant on Earth compared with those arising from gravity. For example, surface tension becomes highly important in low gravity. In a low-gravity environment, it is therefore possible to study the effect of weak forces, especially those arising from electric, magnetic, or acoustic fields, on the shape and compositional distribution of liquids of differing viscosity and surface tension. It may be possible to use these weak forces to control the shape of a melt.

Unique Materials Processing

Ultrapure Materials. It is obvious that a containerless-melted material will be free from any contamination ordinarily introduced from a container. Containerless processing therefore provides a means of preparing ultrapure materials that might be useful as reference standards. Even extremely low levels of impurities in many materials, for example, laser glasses, optical waveguide glasses, and electronic semiconductors, often limit their performance in practical applications. Containerless processing offers an attractive means of preparing such materials. High-purity

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substances that are chemically corrosive and for which no unreactive container material is available on Earth also can be prepared by this technique.

New Vitreous (Glassy) Materials. Vitreous materials normally are prepared by cooling a melt rapidly enough to avoid crystallization. As discussed above, impurities introduced by a container at the melt-container interface can act as nucleation sites (heterogeneous nucleation) for crystallization and prevent glass formation on Earth. The elimination of such container-induced nucleation and crystallization offers the possibility of extending the glass formation region in space to systems that may possess useful properties. The absence of heterogeneous nucleation also increases the likelihood of achieving a high degree of undercooling. In containerless melting, the elimination of heterogeneous nucleation along with the associated undercooling can be used to prepare new glass compositions (nonmetallic and metallic) with improved properties.

Composites. As discussed earlier, a melt on Earth inside the immiscibility region separates into two liquids that segregate into two distinct layers. As there is no buoyancy in low gravity, the segregation of the liquid phases into two layers can be avoided, and a composite material consisting of one phase uniformly distributed in a second matrix phase can be obtained. Such composites could possess unique properties and microstructures. Evidence of a significant reduction in liquid-liquid phase separation and an increasing uniformity of phosphate glasses processed in space has been reported.[30] One can prepare such composites in low gravity using a container, but the preferential wetting of the container material by one phase over the other can cause macroseparation of the two phases. Such a massive phase separation due to preferential wetting has been reported[33] for aluminum-indium (Al-In) alloys in experiments conducted on previous SPAR rocket flights. The Al-rich phase was reported to be surrounded by an In-rich phase that appeared to completely wet the aluminum oxide container used for this experiment.

The efficiency of solid-state optical quantum generators (for example, laser glass) can be increased by increasing the concentration of activator ions in a host matrix. Some laser glass compositions have a nonuniform microstructure that makes it impossible to introduce more than 5% of the activator ions. Higher concentrations of the activator cause it to segregate into one of the phases and this causes concentration quenching of the fluorescence

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output. In low gravity, a significant improvement in structural uniformity is expected such that a higher percentage of activator ions can be incorporated into the glass for a higher lasing efficiency. In an experiment[30] conducted in space by the USSR, as much as 10% neodymium oxide (Nd_2O_3) was incorporated into a laser glass, whereas, more than 2% Nd_2O_3 in glasses made on Earth produced significant concentration quenching.

Special Shaping. Macroballoons. Containerless processing should allow the fabrication of larger diameter glass balloons with the uniformity, sphericity, and concentricity needed for use in nuclear fusion technology as inertial confinement fusion (ICF) targets. The current ICF targets being filled with deuterium-tritium (DT) are only 0.05-0.20 mm in diameter. Thermonuclear fusion is created by irradiating the gas-filled shell with a high-power laser or electron beam. Larger balloons should increase the energy output, but the precise dimensions required for balloons several millimeters in diameter have not been achieved on Earth. Attempts at producing larger balloons have resulted in nonuniform wall thickness and distorted shapes. Containerless processing in low gravity is a potential method of fabricating larger glass balloons of the required dimensional tolerances.

Lenses. Shaping a containerless melt should be possible using either forces used for levitation or by the application of other forces. Materials shaped in this way are unique in that no mechanical stress or distortion is produced in the material as a result of treatments like cutting, grinding, or polishing. Conceptually, it should be possible to fabricate lenses to the required shape without grinding and polishing and thereby retain a pristine, fire-polished surface of nearly perfect optical properties.

Heat and Surface Treatment. Materials commonly are given some type of thermal treatment for the purpose of annealing, tempering, strengthening, chemical machining, flame polishing, and, in certain glasses, for controlled crystallization, coloration, or photochromic action. Depending on the composition, there is a maximum usable temperature on Earth above which the material undergoes appreciable deformation. In low gravity, materials can be heat-treated at higher temperatures because of the absence of gravity-induced flow and distortion. As an example, the preparation of glass-ceramics by controlled crystallization could require heat-treating temperatures close to the glass-softening temperature. Such glasses could not be heat-treated in this way on Earth without risk of consider-

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able deformation. In low gravity, glass-ceramics could be prepared without distortion in a temperature region that is inaccessible on Earth and where new microstructures possessing beneficial properties could be obtained.

Another important application is the mechanical strengthening of a material by the process of ion exchange (i.e., chemically strengthened glass). In this method, a small ion in a material is replaced by a larger ion to produce large compressive stresses on the external surface of the material. On Earth, this process is limited to a temperature at which no significant deformation can occur. In space, the ion-exchange process could be performed at higher temperatures without distortion because the reaction would occur faster. Thicker and therefore more abrasion-resistant ion-exchange layers could be created in shorter times. It is conceivable that divalent cations in glass, whose mobility is too low for exchange at the temperatures usable on Earth, could be exchanged so that even stronger materials could be produced.

Because it is not necessary to support or physically touch any part of a material in low gravity, surface treatments, especially coating the surface of complex shapes, can be performed with great precision. In fabricating ICF targets, it may be desirable to coat the glass balloons containing the DT fuels at high pressure with successive layers of a high-Z (atomic number) metal, a polymer, and a low-Z metal. Low gravity offers advantages in providing coatings of the needed thickness, uniformity, and surface finish for each layer.

Crystal Growth. Semiconductor single crystals constitute the basic components of solid-state electronics. Their efficiency depends on their chemical and structural purity. Single crystals normally are grown from a melt, but contamination from a container and gravity-driven convection always introduce some compositional and structural defects that lower their performance. Promising results have been obtained in the float-zone crystal growth technique where the crystal is grown in a quasicontainerless manner. In this technique, a liquid bridge is formed by melting the central portion of a rod with the melt held in place by surface tension.

On Earth, the length of the melted zone is limited by hydrostatic pressure (weight) and the sagging melt produces nonplanar isotherms near the growth interface. In low gravity, the hydrostatic pressure is eliminated and the float-zone technique for preparing high-purity single crystals can be extended to systems whose surface tension is too low to support zones of useful size on Earth.

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Table 5 Flight sample selection

Sample, composition in mol %	Purpose/objective
1. Al_2O_3	Operational check of acoustic levitator/furnace
2. 39.3%-Ga_2O_3/35.7%-CaO/25%-SiO_2, hot-pressed containing large (~100μm) SiO_2 particles	Study melt homogenization and assess precursor preparation procedure; comparative property analysis with terrestrial sample
3. Hollow glass shell (Pyrex)*	Feasibility study of preparing glass macroballoons
4. 39.3%-Ga_2O_3/35.7%-CaO/25%-SiO_2 devitrified glass with colored droplet on external surface	Study melt homogenization and acquire visual evidence for any mixing in the melt; comparative property analysis
5. 33.3%-Na_2O/66.7%-B_2O_3, glass containing gas bubbles†	Acquire data for bubble behavior (movement, dissolution, coalescence); assess melt rotation
6. 56%-Ga_2O_3/44%-CaO, devitrified glass	Determination of enhanced glass formation; comparative property analysis
7. 50%-PbO/50%-SiO_2, hot-pressed	Study homogenization and assess precursor preparation procedure; comparative property analysis
8. Al_2O_3	Operational check of acoustic levitator at maximum attainable temperature

Note: Al_2O_3 is aluminum oxide; Ga_2O_3 is gallium oxide; CaO is calcium oxide; SiO_2 is silicum oxide; NA_2O is sodium oxide; B_2O_3 is borum oxide; PbO is lead oxide.
*Furnished by Los Alamos National Laboratories, Los Alamos, NM.
†Furnished by R. S. Subramanian, Clarkson College, Clarkson, NY.

Experiments in Progress

The authors of this paper are conducting NASA-sponsored research on the containerless processing of glass-forming melts. Several experiments with different objectives are being conducted on a space shuttle flight by using a single-axis acoustic levitator/furnace. Apart from studying the suitability of the single-axis acoustic levitator

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for processing multicomponent, glass-forming melts in low gravity, the principal objectives of this program are to

- Obtain quantitative evidence for the suppression of heterogeneous nucleation/crystallization in containerless melts
- Study melt homogenization in the absence of gravity-driven convection
- Determine the feasibility of preparing glass macroballoons
- Develop procedures for preparing uncontaminated precursor samples suitable for space experiments
- Perform a comparative property analysis of glasses melted on Earth and in low gravity

A description of the samples to be used and their respective purposes is given in Table 5. Samples 2, 4, 6, and 7 will be used to study glass formation in space by comparing the critical cooling rate for glass formation of samples on Earth with the critical cooling rate of identical samples melted in space where heterogeneous nucleation from a container will be absent. These samples also will be used to compare the properties of Earth- and space-melted glasses. In addition, samples 2, 4, and 7 will be used to study melt homogenization processes in space. The degree of chemical homogeneity achieved in the space-processed samples will be compared with the inhomogeneity initially present in the precursor samples and with the homogeneity of samples processed under identical conditions on Earth. To acquire visual evidence of the presence or absence of fluid flow in the melt, a colored mark has been put on the external surface of sample 4. Any motion of this spot due to fluid motion will be marked by a colored trail. Further evidence of melt mixing and the effect of Marangoni flow will be obtained from sample 5 by observing the motion and movement of internal gas bubbles. Sample 3 will be used to assess the feasibility of preparing glass macroballoons in space.

An important practical task is to determine the suitability of hot-pressed (sintered) precursor samples for containerless melting. Precursor samples made by sintering/hot pressing (samples 2 and 7) have the advantage of being prepared easily without contamination from a container. Thus, the degree of chemical inhomogeneity that can be tolerated in a hot-pressed precursor from which a chemically homogeneous multicomponent melt can be obtained in a reasonable time in low gravity is being determined.

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The overall basis for selecting the sample composition is not particularly critical because the samples are viewed as model systems. The ternary gallia-calcia-silica composition is being used because of its prior use in SPAR experiments.[34] Other glass-forming compositions are typical conventional systems for which needed ground-based property data are available.

A containerless experiment using a three-axis acoustic levitator/furnace has been conducted in space to study glass formation and crystallization kinetics of fluoride glasses[35] and to study the behavior of water droplets.[36]

Conclusion

Low gravity offers unique opportunities to investigate fundamental properties of materials. The high-temperature properties of highly corrosive materials or refractory compounds for which no unreactive container exists can be studied advantageously in low gravity. Properties and processes in melts like surface-tension-driven flow, surface evaporation, heat and mass transfer (diffusion), nucleation and crystallization, and phase separation in immiscible liquids can be studied without the disturbance of gravity, and valuable scientific information can be obtained. The processing of unique materials such as new metallic or nonmetallic glasses, composites with unusual microstructures, ultrapure materials for reference standards, and noncontact shaping are other areas of investigation in low gravity.

Further exploitation of the unique features of low gravity for scientific studies of processes that are usually masked by gravity on Earth likely will lead to a better understanding of basic principles that could have considerable practical value in improving materials-processing technology on Earth.

According to present plans, a manned space station should be operational in the mid-1990s. This will provide a much larger opportunity for low-gravity research and materials processing.

References

[1]Barmatz, M., "Overview of Containerless Processing Technologies," Materials Research Society Symposia Proceedings: Materials Processing in the Reduced Gravity Environment of Space, edited by G.E. Rindone, Vol. 9., 1981, pp. 25-37.

[2]Lacy, L.L., Robinson, M.B., and Rathz, T.J., "Containerless Undercooling and Solidification in Drop Tubes," Journal of Crystal Growth, Vol. 51, 1981, pp. 47-60.

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[3]Rhim, W-K., Saffren, M.M., and Eleman, D.D., "Development of Electrostatic Levitator at JPL," Materials Research Society Symposia Proceedings: Materials Processing in the Reduced Gravity Environment of Space, edited by G.E. Rindone, Vol. 9, 1981, pp. 115-119.

[4]Frost, R.T. and Chang, C.W., "Theory and Application of Electromagnetic Levitation", Materials Research Society Symposia Proceedings: Materials Processing in the Reduced Gravity Environment of Space, edited by G.E. Rindone, Vol. 9, 1981, pp. 71-80.

[5]Whymark, R.R., "Acoustic Field Positioning for Containerless Processing," Ultrasonics, Vol. 13, 1975, pp. 251-261.

[6]Whymark, R.R., Rey, C., Yearnd, J., and Broz, R., "Acoustic Levitation Materials Processing Systems," 17th Aerospace Sciences Meeting, New Orleans, LA, Jan. 1979, pp. 15-17.

[7]Oran, W.A., Berge, L.H., and Parker, H.W., "Parametric Study of an Acoustic Levitation System," Review of Scientific Instruments, Vol. 51, 1980, pp. 626-631.

[8]Oran, W.A. and Berge, L.H., "Containerless Melting and Solidification of Materials With an Aerodynamic Levitation System," Review of Scientific Instruments, Vol. 53, 1982, pp. 851-853.

[9]Rush, J.E., Stephens, W.K., and Ethridge, E.C., "Properties of Constricted Tube Air Flow Levitator," Materials Research Society Symposia Proceedings: Materials Processing in the Reduced Gravity Environment of Space, edited by G.E. Rindone, Vol. 9, 1981, pp. 131-136.

[10]Ray, C.S. and Day, D.E., "Description of the Containerless Melting of Glass in Low Gravity," National SAMPE Technical Conference Series, Vol. 15, 1983, pp. 135-145.

[11]Rey, C., Whymark, R., Danley, T., and Merkley, D., "Present and Future Capabilities of Acoustic Levitation and Positioning Devices," Materials Research Society Symposia Proceedings: Materials Processing in the Reduced Gravity Environment of Space, edited by G.E. Rindone, Vol. 9, 1981, pp. 137-146.

[12]Chaudhuri, A.K., Bonnel, D.W., Ford, L.A., and Margrave, J.L., "Thermodynamic Properties by Levitation Calorimetry. I. Enthalpy Increments and Heats of Fusion for Copper and Platinum," High Temperature Science, Vol. 2, 1970, pp. 203-212.

[13]Cezairliyan, A., "Design and Operational Characteristics of a High Speed (Millisecond) System for the Measurement of Thermophysical Properties at High Temperature," Journal of Research National Bureau of Standards, Vol. 75C, 1971, pp. 7-18.

[14]Margrave, J.L., "Heat Capacities of Liquid Metals Above 1500K," Materials Research Society Symposia Proceedings: Materials Processing in the Reduced Gravity Environment of Space, edited by G.E. Rindone, Vol. 9, 1981, pp. 39-41.

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[15]Colwell, J.H., Cezairliyan, A., and Schmid, L.A., "High Temperature Thermophysical Properties of Refractory Materials from Free Cooling Experiments," NBS Materials Measurements, edited by J.R. Manning, NSBIR 81-2295, June 1981, p. 91.

[16]Wang, T.G., Saffren, M.M., and Eleman, D.D., "Drop Dynamics in Space," Proceedings of the International Colloquium on Drops and Bubbles, California Institute of Technology, Vol. 1, August 1974, p. 266.

[17]Lacy, L.L., Nisen, D.B., and Robinson, M.B., "Containerless High Temperature Calorimeter," NASA Technical Briefs, Spring 1979, p. 85 (also U.S. Patent No. 4,248,038, Feb. 1981).

[18]Cezairliyan, A., "A Dynamic Technique for Measurements of Thermophysical Properties at High Temperatures," Materials Research Society Symposia Proceedings: Materials Processing in the Reduced Gravity Environment of Space, edited by G.E. Rindone, Vol. 9, 1981, pp. 49-57.

[19]Rawson, H., Properties and Applications of Glass: Glass Science and Technology 3, Elsevier, NY, 1980, p. 13.

[20]Onorato, P., Uhlmann, D., and Hopper, R., "A Kinetic Treatment of Glass Formation: IV. Crystallization on Reheating a Glass," Journal of Non-Crystalline Solids, Vol. 41, 1980, pp. 189-200.

[21]Uhlmann, D., "A Kinetic Treatment of Glass Formation," J. Non-Cryst. Solids, Vol. 7, 1972, pp. 337-348.

[22]Uhlmann, D., "Glass Formation," J. Non-Cryst. Solids, Vol. 25, 1977, pp. 42-85.

[23]Yinnon, H. and Uhlmann, D., "A Kinetic Treatment of Glass Formation. V. Surface and Bulk Heterogeneous Nucleation," J. Non-Cryst. Solids, Vol. 44, 1981, pp. 37-55.

[24]Kingery, W.D., Bowen, H.K., and Uhlmann, D.R., Introduction to Ceramics, 2nd Edition, Wiley, NY, 1976, p. 347.

[25]Barta, C., Trnka, J., Triska, A., and Frumar, M., "Recrystallization of Glasses of the Ge-Sb-S System Prepared Under Zero Gravity Conditions," Advances in Space Research, Vol. 1, 1981, pp. 121-124.

[26]Lacy, L.L., Rathz, T.J., and Robinson, M.B., "Containerless Undercooling and Solidification of Bulk Metastable Nb_3, Ge Alloys," Journal of Applied Physics, Vol. 53, 1982, pp. 682-689.

[27]Lacy, L.L., Robinson, M.B., Rathz, T.J., Evans, N.D., and Bayuzick, R.J., "Solidification Studies of Nb-Ge Alloys at Large Degrees of Supercooling," Materials Research Society Symposia Proceedings: Materials Processing in Reduced Gravity Environment of Space, Vol. 9, 1981, pp. 87-94.

[28]Young, N.O., Goldstein, J.S., and Block, M.J., "The Motion of

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Bubbles in a Vertical Temperature Gradient," Journal of Fluid Mechanics, Vol. 6, 1959, pp. 350-356.

[29]Beier, W., Braedt, M., and Frischat, G.H., "Reactions Between Vitreous Silica and Sodium Silicate Glass Melts Under Weightless Condition," Physics and Chemistry of Glasses, Vol. 24, 1983, pp. 1-4.

[30]Petrovskii, G.T., Ryumin, V.V., and Semeshkin, I.V., "The First Step in Space-Age Glass Making," Steklo i Keramika, Vol. 1, 1983, pp. 5-8. (Translated into English by Plenum, NY.)

[31]Annamalai, P., Shankar, N., Cole, R., and Subramanian, R., "Bubble Migration Inside a Liquid Drop in Space Laboratory," Applied Scientific Research, Vol. 38, 1982, pp. 179-186.

[32]Subramanian, R., "Slow Migration of Gas Bubble in a Thermal Gradient," AICHE Journal, Vol. 27, 1981, pp. 646-654.

[33]Gelles, S.H., Markworth, A.J., and Mobley, C.E., "Low G Experiments on Liquid Phase Miscibility Gap (LPMG) Alloys--Materials Experiment Assembly (MEA)," IV European Symposium on Materials Sciences Under Microgravity, Madrid, Spain, April 1983.

[34]Happe, R.A., "SPAR VI Experiment Report: Containerless Processing of Glass Experiment 74-42," NASA TM-82433: Space Processing Applications Rocket, Project SPAR VI Final Report, Oct. 1981, Chap. III.

[35]Doremus, R.H., private communication.

[36]Wang, T.G., "Advanced Containerless Processing Technology," NASA TM-82496: Materials Processing in Space Program Tasks, p. 181.

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Comments on Containerless Processing

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Introduction

The low-gravity environment of space presents unique opportunities to study the fundamental principles of various materials processes and properties. The absence of gravity forces and resultant compositional and thermal convective flows allows for the study of weaker forces (e.g., surface forces), leading to the Marangoni effect and transport-dependent processes (e.g., Ostwald ripening) to be made in a much more carefully defined experimental environment. Similarly, low gravity offers the possibility to perform containerless processing, thus avoiding contamination and nucleation effects produced by the container. The chapter by Day and Ray primarily focuses on this latter advantage. However, the chapter goes beyond this focus to generally discuss the broader importance of the low-gravity environment to materials processing. This commentary discusses aspects of containerless processing given the potential unique advantages of the low-gravity environment relative to other possible Earth-based techniques.

In addition, this commentary addresses ceramic materials properties and processing in the low-gravity environment that are not related to containerless processing. In fact, containerless processing has become somewhat synonymous with ceramic and glass research in space. Unfortunately, it even seems that the interest in developing a containerless-processing technique has been the driving force for the research on ceramics and glass rather than the converse. However, there are several phenomena currently important to the processing of ceramic materials that are ideally suited to study in the low-gravity environment and uniquely important to ceramic processing. Some of these are also discussed.

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It should be noted that there are several generic studies being performed in the areas of crystal growth and metals and alloys that are important to ceramic processing. These studies include an examination of the Marangoni effect on convective phenomena, Ostwald ripening of a second phase, and the effects of thermal and composition gradients on interface stability during crystal growth from the melt. Clearly, these studies will influence ceramic research by improving the understanding of ceramic and glass properties and processing. These studies need not be duplicated with ceramic materials.

Further, the effect of studies in the low-gravity environment on Earth-based processes can be far greater than any actual use of the low-gravity environment for the processing of materials. The virtual absence of both desirable and undesirable convective effects in low-gravity materials processing allows the study of complex processes with the convective complication eliminated. Thus, the possibility of obtaining a better understanding of the process, the importance of convective effects, and the benefits to be gained by minimizing them can lead to significant improvements in Earth-based processing, thus easily justifying the sometimes costly low-gravity experiments.

Levitation Techniques

Four main levitation techniques appear to have been investigated: aerodynamic, electromagnetic, electrostatic, and acoustic. With studies to date,[1] the acoustic levitation technique appears to be the technique of choice particularly for nonconducting materials. However, the discussion of the various techniques is not balanced, reflecting more the emphasis on the development of the acoustic technique rather than the author's emphasis on any one technique.

Aerodynamic Levitation

Aerodynamic levitation is dismissed as unsuitable because the high-velocity gas jets necessary make low-viscosity melts unstable. It is not clear why high-velocity jets are necessary for aerodynamic levitation in a low-gravity environment. One would expect that relatively slow, continuous velocities or pulses of gas would suffice in a low-gravity environment to maintain a liquid or solid sample by viscous drag forces. One could envision a multiaxis system not too dissimilar to the three-axis acoustic levitator for such an aerodynamic system. The requirement for feedback control does not appear to be a severe limitation. It would seem that with various kinds of

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optical positioning schemes one could make possible a relatively simple universal system requiring low power consistent with space operation. The disadvantage of the ambient gas is still present, but the gas composition can be controlled, which may be important for materials that react or decompose.

Electromagnetic Levitation

Even though some nonmetals such as glasses become fairly good conductors at elevated temperatures, electromagnetic levitation appears to be limited to very good conductors and is of little use for ceramics and glasses.

Electrostatic Levitation

The electrostatic technique would seem to offer the advantage that poor conductors could be used. However, at elevated temperatures in a gas atmosphere it would be extremely difficult to maintain charge on the levitated sample. However, this should be possible in a vacuum. Another advantage of electrostatic levitation would seem to be a low power requirement, which is again an advantage in space. Again, the demand for a feedback positioning system at first glance does not appear insurmountable.

Acoustic Levitation

Acoustic levitation appears to offer several advantages, with the major disadvantage being that a gas must be used. However, it would seem that the design of an acoustic levitation furnace would not be so straightforward, particularly for high temperatures. With the velocity of sound varying with the square root of the absolute temperature, strong temperature gradients, which necessarily must exist in such a furnace, would severely distort the standing wave pattern, making design for operation over a wide temperature and atmosphere range seemingly difficult. Furthermore, because the temperature environment is sensitive to sample positioning, any sample drift would distort both the acoustic and thermal fields, perhaps creating an unstable situation. These inherent distortions in the acoustic field imply more than the generation of a standing wave pattern. Ideally, to ensure stability, it would seem that even with the acoustic system some kind of feedback positioning scheme would be necessary, eliminating one of the expected advantages of acoustic levitation.

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Scientific Studies

High-Temperature Property Measurement

Containerless processing offers the advantage of being able to make property measurements on highly reactive or corrosive materials, particularly melts, at high temperatures; techniques have been developed for such measurements. It is not completely obvious, however, that with some clever experimental design, an equivalently good measurement cannot be made by some other technique.[2] High-temperature property data is not being generated in large quantities not because of a lack of experimental techniques but because of a lack of funds to support such data gathering. If funds are made available for low-gravity science research, some of these funds could be used for high-temperature property measurement because of the unique techniques the environment offers. The data may be generated by a unique technique but it is not clear that the data will be unique. It would be interesting to examine data generated on containerless melts in space to determine whether an alternative technique is available.

Nucleation, Crystallization, and Glass Formation

It is correct that containerless melts offer the possibility of studying the nucleation and growth of crystals and glass formation without the complicating effects of container-induced heterogeneous nucleation. However, for many glass-forming systems of interest, heterogeneous nucleation occurs at the free surface between the glass and the ambient atmosphere as well as at the glass-container interface.[3] Containerless processing is only useful for those materials that do not show heterogeneous nucleation at the free surface. Therefore, systems must be carefully chosen for the study of homogeneous nucleation or glass formation in containerless low-gravity environments.[4]

Immiscible Liquids

A low-gravity environment is clearly advantageous for any study of immiscible liquids. Containerless melting becomes important when one of the phases preferentially wets the container, a situation that seems virtually unavoidable. On the other hand, if the surface properties of the two immiscible liquids are sufficiently different so that one preferentially wets a container material, why should their surface tensions also not be sufficiently different so

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that one of the liquids segregates to the surface of the containerless melt? In fact, such surface-tension-driven segregation might be an interesting phenomenon for study if it exists.

Transport Processes and Homogenization

The lack of gravity and the absence of convective flow makes any study of partly diffusive transport processes easier to understand. The effects of surface tension on flow and bubble migration are important effects worthy of study. However, it is not necessarily clear that these effects need to be studied in a containerless melt and indeed some of them are not.

Surface Properties

It is not at all clear that either the low-gravity environment or containerless melts offer any unique advantages for the study of surface properties, with the possible exception of temperature and composition gradients on surface-tension-driven flows.

Unique Materials Processing

Ultrapure Materials

Containerless processing of materials from the melt certainly offers the possibility of avoiding contamination from crucible materials, particularly for high-melting-point materials such as ceramics and glasses. However, similar results can be obtained by variations on the skull-melting process, in which the material acts as its own container and only the center of the material is heated to melting. High-purity magnesium oxide crystals have been made by arc melting (done by Y. Chen, Oak Ridge National Laboratory), nickel oxide and cobalt oxide by arc-image melting (done by N. Peterson, Argonne National Laboratory), and aluminum oxide single and bicrystals have been grown using laser melting (done by J. Haggerty, Massachusetts Institute of Technology). Therefore, containerless melting in the low-gravity environment of space is not necessary.

New Glasses

As discussed earlier, new glasses may or may not be possible by containerless melting. This depends on whether heterogeneous nucleation occurs at the free surface and whether bulk impurities or composition fluctuations can lead to heterogeneous nucleation.

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Composites

The low-gravity environment will indeed allow the fabrication of new composites consisting of constituent materials with differences in density. However, not only wetting of the container but also any difference in liquid-vapor surface energy can also lead to segregation of the two phases as discussed earlier.

Special Shaping

The fabrication of microspheres and shells by containerless processing in low gravity certainly seems feasible. However, the fabrication techniques for other shapes is not obvious without negating some of the advantages of containerless processing.

Surface Treatment

The low-gravity environment certainly appears to have application for surface treatment, such as the ion-exchange process for strengthening glass surfaces. The process can be carried out at higher temperatures, increasing the rate of exchange without gravity-produced deformations. However, the advantages of containerless processing for such surface treatments is not clear.

Crystal Growth

The advantage of the low-gravity environment for crystal growth seems particularly advantageous for the elimination of thermal and compositional convective currents leading to compositional inhomogeneity in the crystal. Again, this is a result of the low-gravity environment rather than the containerless processing.

Other Important Potential Research Areas in Ceramics

Powder Preparation by Gas-Phase Reactions

An extremely promising technique for the fabrication of high-purity, high-technology powders of binary compounds such as silicon carbon for ceramic fabrication is via gas-phase reactions such as[5]

$$SiCl_{4(g)} + CH_{4(g)} = SiC_{(s)} + 4\ HCl_{(g)} \qquad (1)$$

Normally, Earth-based reactions are carried out in flow reactors, making the study of the kinetics of the

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powder nucleation and growth process extremely difficult because of convective currents and particle settling due to gravity. In a low-gravity environment, the reaction could take place by allowing the reactant gases to diffuse into opposite ends of a reaction tube. With only gas diffusion as the major transport process, the nucleation and growth of the particles might be studied much more carefully by a technique such as laser light scattering. If the kinetics of the process can be understood, powders of controlled particle size and particle-size distribution can be designed to optimize the densification process. Given the importance of proper powder characteristics and the emphasis powder fabrication and ceramic materials processing are receiving to increase reliability and reproducibility, this is an important area in which low-gravity experiments would add greatly to the improved processing of high-technology ceramic materials.

Agglomeration of Ceramic Powders in the Gas Phase

Closely related to the study of ceramic powder formation by gas-phase reactions discussed above is the agglomeration of those powders in the gas phase. Small powder particles experience Brownian motion due to collision with gas-phase molecules. The random motion of the particles leads to particle collisions and the formation of agglomerates. Such agglomeration processes generally are undesirable because individual particles are necessary for optimum densification of ceramic materials. However, there are two competing effects in the agglomeration process. One is the motion of the particles, which increases as the particle size decreases and leads to a greater likelihood of collision with other particles in a given time period. The second is the agglomeration (van der Waals) force, which decreases as the particle size decreases. Therefore, there may be an optimum particle size that minimizes agglomeration. The particle size can be controlled by the rate of nucleation and growth. By studying both the particle formation and agglomeration processes there is the possibility of designing an optimum growth rate to minimize agglomeration. Such studies would be virtually impossible to accomplish completely in a 1-g environment.

Ceramic Powder Formation and Agglomeration in Aqueous Systems

Similar experiments to those described above for gas-phase reactions can be performed in aqueous systems. In this case, the attractive van der Waals forces can be over-

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come by charged particles, by applying the principles of electrical double layer theory or the principles of steric hindrance for organic dispersants. Not only could optimum dispersant concentrations be determined but fundamental studies on agglomeration also could be carried out over a range of particle sizes far greater than could be achieved in a one-gravity environment. This would enable the theory to be tested over a much wider range of experimental variables than ever before possible. Furthermore, some recent experiments on two-dimensional agglomeration of powder particles[6] have some interesting implications. These studies may lead to a much-improved understanding of the processes of nucleation and growth and surface diffusion on the atomic scale by observing the behavior of macroscopic colloidal particles interacting under van der Waals and electrostatic repulsive forces. Because of gravity and convective effects, similar studies for three-dimensional particles are extremely difficult in a 1-g environment. However, the low-gravity environment ideally would be suited to such studies, which could lead to not only an improved understanding of colloid dispersion of great interest to improved ceramic powder processing, but also to a much better fundamental understanding of atomic nucleation and growth and surface diffusion processes.

References

[1]Wang, T.G., "Review of the Containerless Processing Technologies and Facilities," Materials Processing in Space, edited by B.J. Dunbar, Am. Ceramic Soc., Columbus, OH, 1983, p. 102.

[2]Kingery, W.D., Property Measurements at High Temperatures, Wiley, NY, 1962.

[3]Bansal, N.P. and Doremus, R.H., "Surface Crystallization of a Fluoride Glass," Comm. Am. Ceram. Soc., August 1983, pp. C132-133.

[4]Neilson, G.F. and Weinberg, M.C., " A Test of Classical Nucleation Theory: Crystal Nucleation of Lithium Disilicate Glass," J. Non-Cryst. Solids, Vol. 34, 1979, pp. 137-147.

[5]Okabe, Y., Hojo, J., and Kato, A., "Formation of Fine Silicon Carbide Powders by a Vapor Phase Method," J. Less-Common Metals, Vol. 68, 1979, pp. 29-41.

[6]Onoda, George, Y., "Direct Observation of Two-Dimensional, Dynamic Clustering and Ordering with Colloids," Phys. Rev. Lett., Vol. 55, 1985, pp. 226-229.

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Combustion Studies In Low Gravity

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Introduction and Background

The central scientific issues in combustion embrace the broad areas of single-phase and two-phase combustion, premixed and unpremixed reaction processes, flame structure and stability, laminar and nonlaminar flows, steady and unsteady combustion processes, and the essential significances of combustion process multidimensionality.

Current understanding of combustion rests heavily on truncated theory and ground-based experiments. Fundamental combustion experiments generally are performed under normal gravitational conditions (g = 1) in Earth-based laboratories. Free-convective-energy and mass-transport processes tend to obscure or transform underlying gravity-free (g = 0) combustion phenomena. Combustion theorists find the multidimensional representation and analytic solutions of multiply coupled transport (radiation-conduction-convection) and comprehensive chemical kinetic processes to be intractable. Accordingly, substantially truncated combustion theory is employed in the interpretation of g = 1 experiments. Typically, one-dimensional g = 0 theory is used to model non-one-dimensional, g = 1 experimental data.

A compelling basis for carrying out combustion experiments under low-gravity conditions ($g \approx 0$) derives from unsatisfied scientific needs for combustion information that Earth-based laboratories have not provided. Under reduced gravitational conditions, stable arrays of combustible particulates and drops could be created for study of combustion characteristics not heretofore observed.

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Asymmetries in the burning of a single particle or a liquid drop can be attributed to reasons other than "gravity," and tenuous arguments invoked to derive zero-gravity flame propagation and extinction characteristics from unit-gravity observations of "upward" and "downward" flame propagation experiments could be discarded. The energy, mass transport, and chemical kinetic interactions that determine oscillatory, flow, and autoignition behavior in closed combustible systems could be assessed more successfully. The broad areas of high-pressure combustion and extinction phenomena, so significant in current energy conversion and safety technologies, could be studied from a fundamental perspective. The multidimensional effects generally associated with gravity-induced body forces could be suppressed, thereby permitting more tractable analysis with closer correspondence to experimental ($g = 0$) observation.

Low-gravity combustion research is not new. During the decade of the 1950s, experimental studies of combustion under low-gravity conditions were carried out by University of Tokyo workers who demonstrated that liquid fuel drops could burn in a spherically symmetric fashion, in accordance with simple, gravity-free combustion theory.[1,2] With the advent of NASA's requirements for knowledge of combustion processes in space environments, the 1960s saw various U.S. workers start to employ drop tower (and related) facilities to study gravitational effects on several combustion phenomena.[3]

In 1973, NASA commissioned a study concerned with examining "the physical bases and scientific merits of combustion experimentation in a space environment." The study was broad-ranged, solicited the views of the combustion science community's many workers, and was completed with the issuance of a summary report in 1974. Ground-based combustion research findings of the 1974-84 period have not diminished the recommendations and conclusions derived from the 1973-74 study. To quote directly from Ref. 4:

> The review of combustion experimentation (and modeling which could benefit from the availability of a space laboratory) reveals one theme that appears to dominate all others. Extensive and systematic experimentation on the range $0 \leq g \leq 1$ is viewed as essential to the development of the understanding required in virtually all the major fundamental areas of combustion. Current theory has not been adequately guided by experiment. Current (drop tower) facilities for

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$0 \leq g \leq 1$ experimentation have an important role to play in future studies. But these roles are necessarily limited. Only an orbital space laboratory can provide the scales of time and space necessary to exploit substantially the scientific goals of combustion experimentation in a space environment. These conclusions apply for:

(1) Premixed Flame Propagation and Extinction Limits;
(2) Theory of Noncoherent Flame Propagation;
(3) Upper Pressure Limit Theory of Ignition and Flame Propagation;
(4) Autoignition for Large Premixed Gaseous Systems;
(5) Cool Flames in Large Premixed Gaseous Systems;
(6) Burning and Extinction of Individual Drops or Particles, Over Very Large Ranges of Pressure;
(7) Ignition and Autoignition of Clouds of Drops and/or Particles, Over Very Large Ranges of Pressure;
(8) Two Phase Combustion Phenomena Involving Large Liquid-Gas or Solid-Gas Interfaces;
(9) Radiative Ignition of Solids and Liquids;
(10) Pool Burning and Flame Propagation Over Liquids;
(11) Flame Spread and Extinction Over Solids;
(12) Smoldering and Its Transition to Flaming (or Extinction);
(13) Laminar Gas Jet Combustion;
(14) Coupling or (Decoupling) of Convectively-Induced Turbulence Involved in Various Combustion Phenomena;
(15) Transient Responses of Flames to Time-Dependent (Effective) Gravitational Fields

This is a partial listing of the many valuable experimental and theoretical programs that can be carried out with the essential facilities provided by a Space Environment. Several of these programs show particularly outstanding promise.

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In this latter category must be included the areas of:

(1) Extinction Limits in Premixed and Unpremixed Gases;
(2) The Many Diverse Areas of Two Phase Combustion, Particularly the Combustion of Single Drops and Particles, Arrays of Solid Fuel Elements, and Liquid Pools.

The extent to which other noted (or uncited) combustion studies will revolutionize our understanding of the Fundamentals of Combustion depends largely on the ingenuity of experimenters and theorists who have yet to address the scientific opportunities that space-based combustion experimentation can provide.

The 1974-85 period has seen many contributions to combustion theory and experiments concerned with the centrally important problems considered in the 1973-74 study. These have served to strengthen the conclusions of Berlad et al. regarding the need for low-gravity combustion experiments.

This paper briefly reviews the status of major areas of combustion science for which low-gravity studies promise to provide otherwise unobtainable sets of needed results.

Why Low-Gravity Combustion Experiments

Low-gravity combustion experiments may prove useful because under low-gravity conditions, natural convective processes are suppressed, gravitational settling in two-phase combustibles is suppressed, and spatial homogeneity of quiescent, nonuniform-density combustibles may be achieved. Where turbulence-inducing mixing processes are employed (at g = 1) to achieve spatial homogeneity of non-uniform-density combustible mixtures, low-gravity conditions permit the maintenance of spatial uniformity while turbulence decays. Some important combustion experiments now carried out at normal gravitational conditions may be compromised in essential ways. In some cases, these compromising features can be eliminated by the use of low-gravity experimentation. In other cases, g = 1 combustion experiments involve natural convection-coupled effects that are not adequately understood. In such cases, low-gravity experimentation may be employed to help resolve these effects. In some other cases, needed combustion experi-

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ments are simply not achievable at g = 1 but are feasible at reduced gravitational conditions. In all instances, however, the use of low-gravity combustion experimentation represents a powerful tool for the solution of centrally important issues where g = 1 experimental/ theoretical attempts have been (and promise to be) inadequate.

For more than a decade, NASA-sponsored studies[4-21] have followed the pioneering work of Kumagai and Isoda in systematically exploring the effects of gravity on combustion. In the following several cases, we examine the special significance and value of low-gravity experimentation for each characteristic case. In general, information to be derived has not been obtainable by other means.

Premixed Gaseous Flame Propagation and Extinction

Previous studies at normal gravitational conditions have shown[4] that upward and downward premixed gaseous flame propagation are substantially different and that natural convection dominates upward flame propagation mechanisms in the neighborhood of the flammability limits. It is recognized that flammability-limit theory is not fully developed and that premixed flame propagation and extinction theory can be placed on a firmer foundation through experimental studies that suppress natural convective effects. The resolution of these flame-theoretical issues is important to an understanding of two-phase (premixed) combustible systems and to single-phase premixed systems.[12,18,19]

Premixed Particulate Cloud Flame Propagation and Extinction

Premixed, uniform, quiescent clouds of combustible particulates (in a gaseous oxidizer) are difficult or impossible to achieve in Earth-based laboratories. This is particularly true for particulates of substantial size.[22] Development and testing of flame propagation and extinction theory for such systems requires first that reliable experiments be achieved for quiescent, premixed, homogeneous systems. The classic two-phase flammability studies developed at the U.S. Bureau of Mines[23] and elsewhere have provided important bases for comparing the relative flammabilities of various combustibles. Unfortunately, it has been impossible to establish the quiescent, uniform clouds of particulates that are required to adequately characterize the preignition states of these two-phase combustible systems. These difficulties (at g = 1) derive directly from particle-settling effects and/or from mixing-induced tur-

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bulence effects. It has been argued[22] that these g = 1 difficulties can be alleviated through low-gravity experimentation. Once two-phase premixed flame propagation and extinction data are obtained (at reduced gravity), theoretical resolution of the differences between premixed single-phase and premixed two-phase flame propagation and extinction theory becomes more promising. Planned studies at reduced gravitational conditions include those for lycopodium-air, cellulose-air, and coal-air particulate clouds.

Smoldering

One of the most interesting combustion phenomena is smoldering. This phenomenon appears to sustain a number of characteristic processes at normal gravitational conditions: steady and unsteady smoldering, extinction, and the transition to flaming combustion. There is the complex interaction of two-phase pyrolysis and oxidative kinetics.[24] Radiative, molecular, forced, and free-convective transport processes interact in poorly understood ways. All characteristic rates, chemical and transport, are slow compared to those that typify flaming combustion. Both experimentally and theoretically, it has been difficult to describe the roles of each of the interacting processes. No comprehensive theory is available that prescribes both the quasisteady smoldering process and the critical conditions for transition to extinction or flaming. Can smoldering exist in the absence of natural and/or forced convection? There is a need to address this and related central issues associated with this important combustion phenomenon. Low-gravity experimentation is expected to help address this need.

Combustion of Individual Drops and Particles

The classic work of Kumagai and Isoda[1] has served to stimulate subsequent studies with the combustion of individual drops and particles. In the absence of a gravitational field, spherically symmetric burning has been dramatically demonstrated.[1] But questions remain that require further experimentation at reduced gravitational conditions. One may note[17] the significant areas of the general unsteadiness of single-drop combustion, nonsphericities in ignition and combustion, the interactions of nonspherically symmetric drop vaporization-combustion and drop motion, flame extinction, and explosive extinction of a burning single drop.

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Radiative Ignition of Condensed-Phase Fuels

Current theory and experiments show that (at g = 1) very large radiative flux rates imposed on very large planar-surfaced liquids or solids lead to short ignition delays that do not depend substantially on natural convective processes.[25,26] However, for low radiative flux rates and for small fuel-sample sizes, natural convective processes can be important. In the limiting case where radiative flux rates are inadequate to achieve ignition, free convective losses to a cold atmosphere are centrally important.[25] Accordingly, there is a complex interplay of radiative, convective, and molecular transport (with vaporization, pyrolysis, and oxidation kinetics) that prescribes limiting radiative-induced ignitability at normal gravitational conditions. Understanding of these complex, limiting ignitability conditions could be enhanced greatly through research that would permit the suppression and/or control of natural convective effects. Low-gravity combustion experimentation promises to provide otherwise unobtainable insights into this important class of problems.

Large-Surface Combustion and Extinction

Two-phase combustion processes involving a gaseous oxidizer and large condensed-phase combustible materials have been studied extensively under normal gravitational conditions. Complex flame propagation and extinction phenomena are observed. Gravitational collapse of partially burned solid-fuel arrays sometimes tends to compromise the investigator-selected conditions for the unburned medium. Gaseous natural convective processes are generally so prominent as to obscure the roles of chemical kinetics and of other transport processes. Natural convective processes frequently determine the location of effective control surfaces at which preselected gaseous oxidizer conditions are best known. In the propagative burning of liquid pools (and of melting solids) surface-tension-induced convection processes[27] are thought to play an important role. To be able to modify, suppress, or control one or more of these effects through low-gravity combustion research seems attractive. More tractable theory can then be applied to liquid pool burning phenomena that promise to be less complex.

Boundary-Layer Combustion

Boundary-layer combustion may be supported by flow of an oxidizing gas over a flat plate that serves to supply

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(by fuel vaporization or by fuel injection) gaseous fuel for the combustion process. At normal gravitational conditions operating on flow over a flat horizontal plate, current analysis shows[10] that the cross-stream buoyancy-induced body force acts to effectively produce a streamwise pressure gradient in the fluid adjacent to the plate surface. For an upward-facing plate, a favorable pressure gradient is derived that tends to accelerate the flow, relative to the corresponding gravity-free case. Flow deceleration is prescribed for a downward-facing plate. These gravitational effects induce changes in boundary-layer structure and flame standoff distances. It is expected that boundary-layer combustion under low-gravity conditions may serve to verify these current theoretical concepts and to resolve observed inconsistencies between experiments conducted at g = 1 and theory that neglects gravitational effects.

Counterflow Diffusion Flames

Flame systems involving unpremixed gaseous fuel and oxidizer generally are referred to as diffusion flames. Extinction conditions for counterflow diffusion flames have been of great interest and generally analyzed in terms of a critical strain rate or Damkohler number for extinction.[28,29] The criticality conditions for stagnation regime extinction suggest a limiting ratio of a characteristic chemical kinetic time to a characteristic fluid dynamic time. The early analyses and experimental results[28-30] consider the counterflow diffusion flame experiment to be independent of gravity and to be one-dimensional. More recent experimental investigations[31] (at g = 1) indicate that buoyancy forces as well as apparatus scale are important determinants of extinction, particularly at low strain rates. Low-gravity experimentation of this kind is not yet available, nor are there analytic results that account for (g = 1) gravitational and nonadiabatic effects.

Nonflowing Premixed Combustible Media

A broad class of important combustion phenomena are observed, at normal gravitational conditions, in nonflowing premixed systems. This class includes gaseous and two-phase autoignition and explosion processes, kinetic oscillations associated with the low-temperature oxidation of carbon monoxide (CO), and thermokinetic oscillations associated with the oxidation of hydrocarbons.[11,16] For all of these phenomena, apparatus walls (and associated boundary conditions) play an important role in heat and mass transport. Heat and mass transport between wall and gaseous

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medium, as well as the heterogeneous chemical kinetic processes at the walls, have been found[11,16,28] to strongly influence both qualitative and quantitative characteristics of these phenomena. Moreover, there exists a corresponding set of autoignition (and other?) phenomena for premixed clouds of particulates. These two-phase premixed combustion processes cannot be studied in a similar way at g = 1 because of the gravitational settling of particulates and/or the mixing-induced turbulence required to achieve reasonably uniform clouds of particulates. These problems are particularly severe for the case of large particles (e.g., of the order of 50 μm or larger), mixed particle sizes, and mixed particulate materials. The specific, significant absence or presence of natural convection may determine whether an autoignition phenomenon is to be adequately characterized as a one-dimensional or as a multidimensional phenomenon. Combustion experimentation at low-gravity conditions may be used to deal with these two-phase problems.[22] For selected members of this class of problems, a number of single- and two-phase combustion phenomena are discussed below. The role of low-gravity research in resolving essential theoretical and experimental issues is emphasized.

Combustion Phenomena in Nonflowing Premixed Systems

The systems to be discussed here generally are considered to involve the least complex combustion theory and some of the cleanest and easiest-to-define experimental conditions. An understanding of these phenomena is fundamental to an understanding of more complex combustible systems involving forced convective flows. Although g = 1 experimental conditions may be of great interest, current theoretical representations generally are fashioned for g = 0 conditions, for which experiments have not yet been performed. This inconsistency is compounded by the difficulty or inappropriateness of actually performing suitable g = 1 experiments.

Autoignition Phenomena in Premixed Gaseous Media

The constitutive equations for thermokinetic processes in premixed gaseous media generally include an energy equation, a set of chemical kinetic rate equations, mass or species conservation equations, and an equation of state.[16] For a gravity-free field, these are of the form

$$\rho c_v(\partial T/\partial t) = \nabla \cdot [\lambda \nabla T + I] + \sum_{j=1}^{r} R_j \quad \Delta_j \qquad (1)$$

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and

$$\xi_{j1} + \xi_{j2} + \xi_{j3} \xrightarrow{\quad k_j \quad} \xi_{j4} + \xi_{j5} + \xi_{j6} + \Delta_j \qquad (2)$$

$$\text{for } j = 1, 2, \ldots, r$$

and

$$\partial c_i/\partial t = \nabla \cdot (D_{i,m} \nabla c_i) + \sum_{j=1}^{r} c_{ij}^{III} \qquad (3)$$

$$\text{for } i = 1, 2, \ldots, n$$

and

$$pv = \sum_i c_i RT \qquad (4)$$

where c_i is the volumetric mole concentration of the i^{th} chemical species; i = 1,2,_____,n; c_{ij}^{III} is the volumetric molar rate of production of the i^{th} chemical species by the j^{th} kinetic process; j = 1,2,_____,r; c_v is the specific heat at constant volume. D is a diffusion coefficient; I is a photochemically insignificant (thermal) radiative flux density; k_j is the rate constant for the j^{th} kinetic process; R is the universal gas constant; R_j is a molar reaction rate corresponding to the species and energy release Δ_j; T is the absolute temperature; Δ_j is the molar heat of reaction for the j^{th} irreversible kinetic process; λ is a local thermal conductivity; and ξ_{jq} are the concentrations associated with the q = 1,2,____,6 species that participate in the j^{th} kinetic process. Equations (1-4) ignore any transfer of heat and mass that may derive from natural convective effects peculiar to these experiments.[33,34] The constitutive Eqs. (1-4) have not been generalized and applied to autoignition observations at g = 1. Moreover, the roles that walls play for both heat and species conservation appear to be obscured by natural convective processes. This is particularly true where heterogeneous chemical kinetics (wall chemistry) may play a significant role in autoignition.[35,36] In all of these previous studies, application of Eqs. (1-4) in their multidimensional form has not been made. In fact, reliable specification of the specific reactivity to be assigned to the various radial boundary conditions has not been achieved. This is due to, in part, the usual truncation of Eqs. (1-4) into a set of one-dimensionalized equations. But even if Eqs. (1-4) were used in their most general form, they are appropriate only in a gravity-free field.

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The variety of heterogeneous chemical kinetic effects (on autoignition) that awaits low-gravity investigation is enormous. The specific reactivities of chemically reactive walls are not deducible, where radial transport properties are unknown or ill-defined (natural convective effects). The very nature of this important combustion process is lost in the ad hoc representations currently employed to deal with the specific reactivity of a wall effect. Typically, kinetically significant radial boundary conditions are not imposed (by current workers) on Eqs. (1-4). Rather, heterogeneous wall chemistry is couched in homogeneous chemical kinetic schematics[34-36] of the classical form

$$A \xrightarrow{k_{AW}} \text{Wall} \tag{5}$$

and

$$B \xrightarrow{k_{AW}} \text{Wall} \tag{6}$$

where A and B are taken to be chemically important species. One-dimensionalization of Eqs. (1-4) with the use of truncated analytical forms such as Eqs. (5) and (6) still requires detailed knowledge of radial transport properties. For noncatalytic walls acting as perfect species sinks, and in the absence of free convection, $k_{A,W}$ can be approximated

$$k_{A,W} \simeq \frac{12D}{d^2} \tag{7}$$

Clearly, natural convective effects at g = 1 make Eq. (7) inappropriate. Significant heterogeneous kinetic processes also serve to make Eq. (7) inappropriate.

The current experimental and theoretical situation with autoignition phenomena may be summarized as follows: extensive experimental data obtained at g = 1 demonstrate the important roles that natural convective transport of heat and mass can play in the determination of the autoignition phenomenon. The specific reactivity of walls is not adequately described as a result of ill-defined free-convective effects and the limiting features of truncated representations of the multidimensional problem. More sophisticated computational approaches coupled with low-gravity experimentation promises to provide both better understanding of autoignition and deduction of the specific reactivities of kinetically active walls.

The rich variety of fundamental autoignition phenomena extends well beyond "explosions." Other autoignition phenomena (observed at g = 1) include kinetic oscillations

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in CO oxidation, thermokinetic oscillations in hydrocarbon oxidation, glows, and multiple ignitions. Two-phase systems are relatively unexplored. None of the (g = 1) observed reaction trajectories to date have been experimentally characterized multidimensionally. None have been observed at g = 0. All have been characterized analytically as one-dimensional g = 0 phenomena.

Some further discussion is offered in the following sections. It is useful to note first the g = 0 analytic characterizations possible for the stationary states considered for autoignition phenomena. For two-variable stationary conditions (e.g., temperature and one chemical intermediate species, x and y, respectively) characteristic stability conditions include stable and unstable nodal points (Figs. 1 and 2), unstable saddle point (Fig. 3), and stable and unstable foci (Figs. 4 and 5). Criticality conditions often are associated with the bifurcative merging of a stable node with an unstable saddle point (Fig. 6).

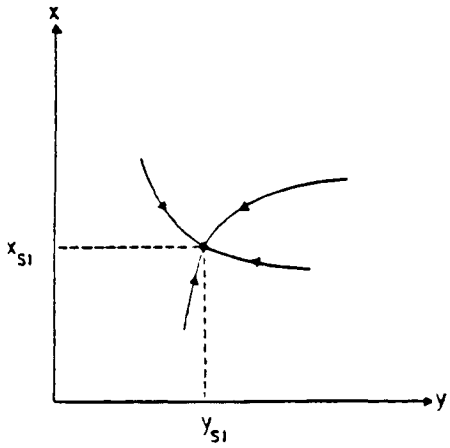

Fig. 1 A stable nodal point.

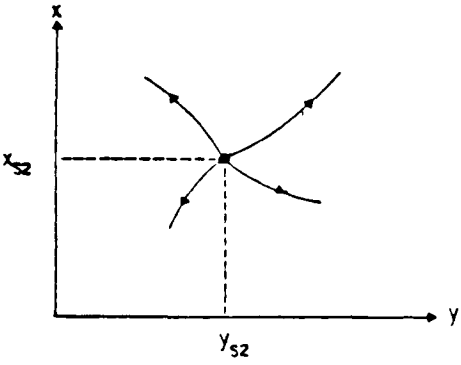

Fig. 2 An unstable nodal point.

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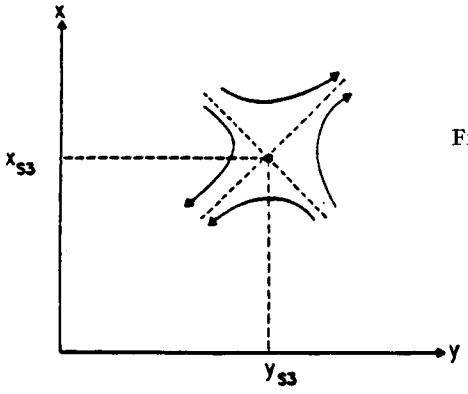

Fig. 3 An unstable saddle point.

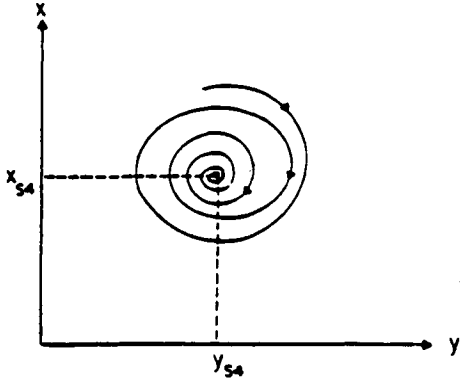

Fig. 4 A stable focus.

Oscillatory processes are associated with foci (Figs. 4 and 5) that approach centers (Figs. 7 and 8). This apparent complexity understates reality. Observed g = 1 systems importantly involve multiple intermediates, multidimensional secondary flows and nonstationary states for which nonlinear time-dependent trajectories are more characteristic.[16]

Autoignition Phenomena in Premixed Clouds of Particulates

For purely gaseous media, Earth-bound experimental procedures to create uniform quiescent mixtures of fuel and oxidizer are trivially routine. For clouds of particulates, establishment of Earth-bound uniform clouds of quiescent fuel particulates (in a gaseous oxidizer) has not been possible. This is particularly the case for large (practical) size particulates. For particulates whose gravitational settling velocities are significant, vigorous mixing techniques are required[22] to achieve uniform particulate

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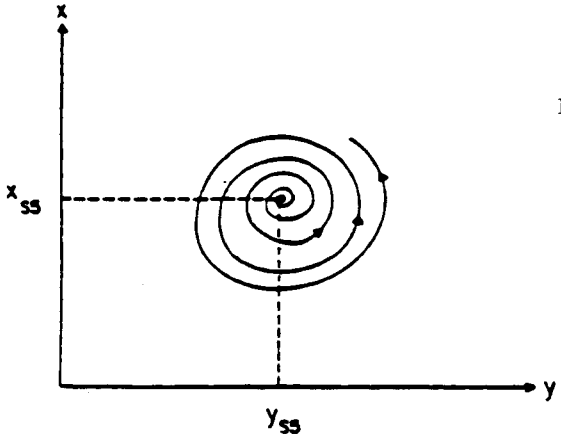

Fig. 5 An unstable focus.

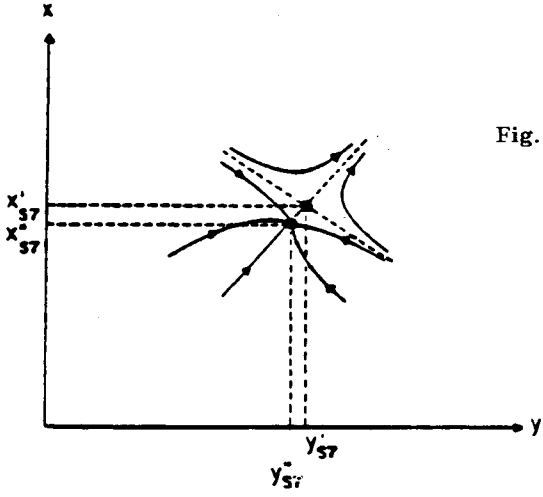

Fig. 6 Onset of a bifurcation.

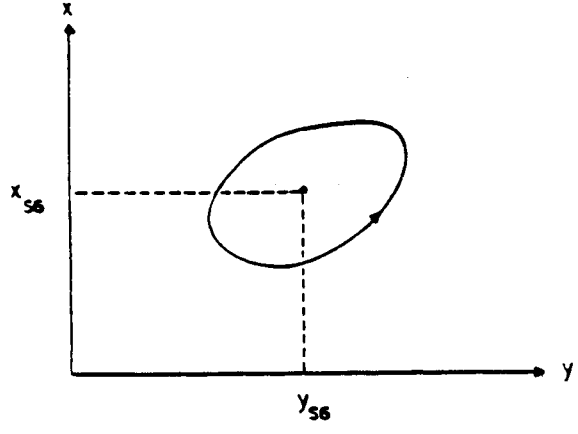

Fig. 7 A center.

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concentrations. Under highly stirred conditions, transport properties of the medium are ill-defined. The decay of mixing-induced turbulence is slow,[22] and (at g = 1) particulate settling processes proceed as mixing-induced turbulence decays slowly. Extensively documented studies of "explosions" in two-phase systems (at g = 1) have served to provide important qualitative insights into the relative combustibility of a broad variety[37,38] of particulates. Unfortunately, the g = 1 data on two-phase "autoignition" do not lend themselves to analysis. In general, experimental conditions are poorly defined. Uniformity of particulates is questionable, particle-gas velocity defects are operative, and the transport properties are transient and unknown. In view of the fundamental and practical importance of two-phase combustible systems, the study of the autoignition of uniform, quiescent clouds of particulates appears necessary. Current theory[21] for two-phase autoignition has not been experimentally tested. Normal gravitational conditions present great difficulties, and low-gravity experimental investigations have not yet been performed. For the case of clouds of 1-μm zirconium particulates, the analyses presented in Ref. 21 have been employed to illustrate the effect of gravitationally induced heat-loss processes on the cloud autoignition condition (Fig. 9).

It is not known whether the autoignition phenomena yet to be observed for two-phase premixed systems (in low gravity) will prove to be as diverse as those associated with premixed gases.

Kinetic Oscillations in Carbon Monoxide-Oxygen Combustion

There exist extensive experimental studies of the low-temperature oscillatory oxidation of CO. These studies (e.g., Ref. 32 and 33) all were performed at normal gravitational conditions. Although the combustion process is

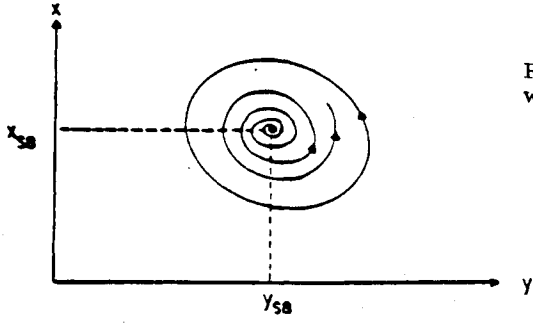

Fig. 8 An unstable focus within a stable limit cycle.

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slow, natural convective transport of heat and mass is an ever-present concern. Current theory emphasizes the importance of chemically reactive wall mechanisms. Equations such as Eq. (5) are used as essential descriptors for wall chemistry involving [H], [O], [OH], [H_2O], and [H_2O_2] species. Indicated above are the inadequacies of equations of this form when applied to Earth-bound observations of combustion phenomena in closed vessels involving chemically reactive walls. The characteristic period of this oscillation phenomenon is so long (of the order of several seconds) that g = 0 experimentation in spherical or long cylindrical vessels would permit spectroscopic space-and-time resolution of chemical species concentrations in a well-defined one-dimensional or two-dimensional reactor. Accordingly, convection-free combustion dynamics may be observed and analyzed. Truncation of radial boundary condition information then would not be necessary. Specific surface reactivities may then be properly invoked. No such low-gravity experiments have yet been performed.

Thermokinetic Oscillations in Hydrocarbon-Oxygen Combustion

The phenomenological features that prescribe oscillations in the low-temperature combustion of hydrocarbons are thought to be very different from those associated with CO oxidation. At about 600 K, a small number of hydrocarbon oxidation cycles (typically less than 10) are

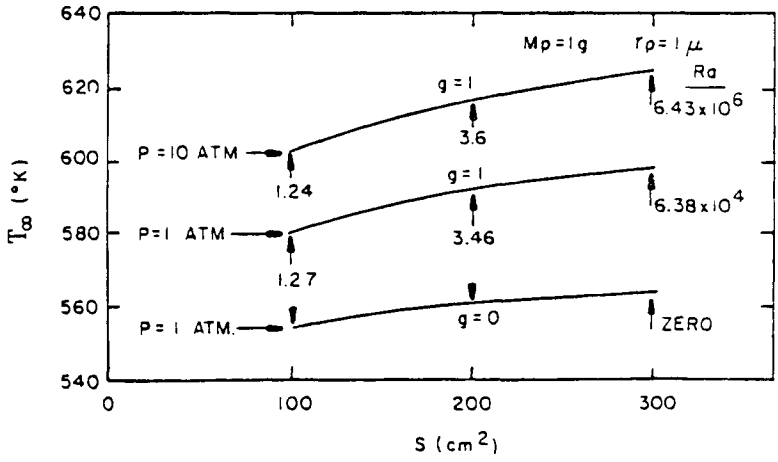

Fig. 9 Free convective losses and zirconium cloud autoignition temperature as a function of vessel size and ambient pressure.

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observed in closed vessels,[39] with temperature rises per pulse of about 5 K to 200 K. Oscillatory hydrocarbon oxidation is thought to be thermokinetic with the oscillatory process dependent on the heat-transfer rates between the reactive medium and the reactor walls and the interaction of these heat losses with "negative temperature regime" chemistry.[32] Natural convection dominates these heat-transfer rates, in the absence of other, experimenter-imposed effects. Inasmuch as natural convection for this transient effect is not well understood, attempts to employ controlled heat-transfer rates through vigorous stirring have been employed.[39] Without a knowledge of these unsteady heat losses, analysis of this class of phenomena is not possible.[40] Yet, at normal gravitational conditions, the currently employed heat-transfer correlation of the form[39]

$$q = \ell \quad (S/V) \quad (\bar{T} - T_w) \tag{8}$$

must be considered unreliable. In Eq. (8), ℓ is an estimated effective heat-transfer coefficient associated with the unsteady process, (S/V) is the surface-to-volume ratio, and $(T - T_w)$ is an estimated spatially averaged characteristic temperature rise.

If this experiment were done under reduced-gravity conditions, without stirring and natural convection, there would be no necessity for recourse to questionable heat-transfer correlations. The complete set of constitutive equations may then be applied. Detailed space-time species and temperature structures of such slowly varying processes are experimentally accessible in low gravity. To date, no such experiments have been performed.

Final Observations Regarding Autoignition Studies

This purposeful emphasis on the unexplored complexity of g = 0 autoignition processes helps to illustrate that the class of combustion phenomena that are experimentally and theoretically most tractable has not been adequately explored at g = 1. Generic difficulties heavily limit the ability to rectify this situation through g = 1 experimentation alone. What conclusions may be drawn regarding the status of other, more complex combustion processes, and the contributions that fundamental low-gravity combustion studies can offer?

Theoretical and Computational Needs in Support of Low-Gravity Experimentation

An important finding derived from available low-gravity and other combustion studies relates to the

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essential multidimensionality of real g = 1 combustion phenomena. Only for the cases of selected g = 0 processes can the possibility of purely one-dimensional phenomena be considered. In some cases, one-dimensional approximations can prove to be physically and mathematically useful. Nevertheless, it is evident that expanded capability and use of computational methods[41] need to be encouraged. Results so obtained need to be reconciled with analyses that have to be less encumbered by truncated physical models. It may be expected that the combustion observations derived from low-gravity experiments will help to bring truncated mathematical analysis and more comprehensive numerical computations to a much closer correspondence than is now the case. The essential multidimensionality implied by gravitational and other effects on combustion appears as an ever more pervasive observation. Several examples are cited.

Counterflow diffusion flame structures classically have been analyzed as one-dimensional and insensitive to body

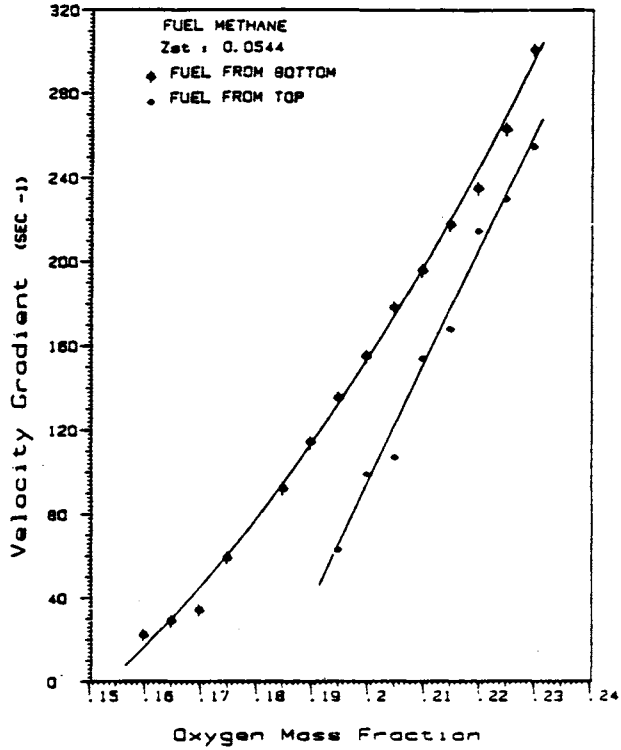

Fig. 10 Counterflow diffusion flame extinction conditions as influenced by gravitational effects (Ref. 31).

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forces and omnidirectional transport processes. Detailed chemical kinetics typically are simplified to accommodate analytic modeling[28,30]. Recent experiments reveal that there are substantial gravitational effects on critical velocity gradients for extinction[31] and that observed flame structures are multidimensional. These results are illustrated in Fig. 10.

Radiative ignition of solids lends itself to simplified one-dimensional mathematical modeling,[26] whereas commonly encountered experimental results display the multidimensionality of the phenomenon and the important roles of gravitationally induced mixing processes. In practical systems, gravitational effects and finite sample sizes are essential[42] to prescription of the critical steady-state radiative flux density below which an irradiated sample cannot be ignited.

The growth rate of the enormous body of one-dimensional, gravity-free representations of gravity-influenced, multidimensional combustion phenomena appears to be undiminished. The first four 1985 issues of Combustion and Flame contain some 20 papers within which multidimensionality appears to be an absent consideration. In some cases, such omissions may prove to be useful approximations. Typically, justification awaits more general analysis and/or experiments whose observed multidimensionality can be interpreted with success. Suppression of natural convection effects promises to assist in these endeavors.

Achievement Opportunities Through Low-Gravity Combustion Research

During the past decade, a number of U.S. workers have initiated combustion studies aimed at exploiting low-gravity environments to conduct otherwise inaccessible experimental research. In each case, the principal investigator and peer reviewers recognized both the uniqueness and central importance of anticipated results. Under the aegis of NASA's Microgravity Science and Applications Division, the following investigations are in progress:

- F. A. Williams, Princeton University
  Droplet Burning
- R. A. Altenkirch, University of Kentucky
  Solid Surface Combustion
- A. L. Berlad, University of California, San Diego
  Particle Cloud Combustion

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- R. B. Edelman, Science Applications, Inc.
  Gas Jet Diffusion Flames

- R. A. Strehlow, University of Illinois
  Effect of Gravity On A Lean Limit Flame

- P. D. Ronney, NRC Fellow at NASA-LeRC
  Effect of Gravity on Near-Limit Behavior In Laminar Premixed Gas Flames

- P. Pagni & C. Fernandez-Pello, University of California, Berkeley
  Smoldering Combustion

- W. Sirignano, University of California, Irvine
  Gravity Effects On Liquid Fuel Pool Fires: Ignition, Flame Spread and Pool Burning

- K. Sacksteder, NASA-LeRC
  Spacecraft Fire Safety

The first space-shuttle-based combustion experiments were scheduled to commence in 1985. Precursor experiments employing NASA drop-tower and aircraft facilities already have proved to be useful. NASA drop-tower facilities proved to be important ongoing contributors to low-gravity combustion research. Many of the insights provided in recent contributions by Williams,[13] Strehlow,[12] Altenkirch,[20] and others were developed with the help of drop-tower experimentation. The work reported in Ref. 19 benefited greatly from the accessibility of NASA drop-tower facilities. Premixed methane-air flame flammability limits (at low-gravity) have been observed in several different apparatus.[12,18] A range of low-gravity drop-burning characteristics (not previously reported in the classic work of Kimagai and Isoda[1]) have been observed and/or considered.[13] Flame-spreading rates over solids, with and without suppressed gravitational effects, have been observed.[20] Radiative transport rates for stabilized two-phase flames have been measured in drop-tower experiments and associated flame structure and stability characteristics have been observed.[19] These and related studies provide essential facts regarding the multidimensional characteristics of a range of combustion processes. The nine projects listed above have yet to exploit the major opportunities identified for each. These nine projects attack only a small portion of the body of combustion information awaiting resolution through low-gravity research.

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Conclusion

This brief review has noted several central issues in combustion science that await resolution through low-gravity combustion research. Low-gravity combustion studies promise to eliminate problems that derive from gravitational settling and ill-defined and/or unwanted mixing processes, thereby permitting well-characterized experiments and tractable analytic problems. Where $g = 0$ theory and experiments can be brought to reliable correspondence, they both can be used as essential foundations for understanding more complex systems that derive for $g > 0$.

References

[1]Kumagai, S. and Isoda, H., "Combustion of Fuel Droplets In A Falling Chamber," Proceedings of the Sixth Symposium (International) on Combustion, Reinhold, NY, 1957, pp. 726-731.

[2]Isoda, H. and Kumagai, S., "New Aspects of Droplet Combustion," Proceedings of the Seventh Symposium (International) on Combustion, Butterworths, London, 1958, pp. 523-531.

[3]Hall, A.L., "Observations on The Burning of a Candle at Zero Gravity," Report No. 5, Naval School of Aviation Medicine, 1964. (Available from DDC as AD-436897.)

[4]Berlad, A.L., Huggett, C., Kaufman, F., Markstein, G.H., Palmer, H.B., and Yang, C.H., "Study of Combustion Experiments in Space," NASA CR-134744, 1974.

[5]Edelman, R.B., Fortune, O.F., Weilerstein, G., Cochran, T.H., and Haggard, J.B., "An Analytical and Experimental Investigation of Gravity Effects Upon Laminar Gas Jet Diffusion Flames," Proceedings of the Fourteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1973, pp. 399-412.

[6]Haggard, J.B. and Cochran, T.H., "Stable Hydrocarbon Flames in a Weightless Environment," Combustion Science and Technology, Vol. 5, 1972, pp. 291-298.

[7]Cochran, T.H. and Masica, W., "Effects of Gravity on Laminar Gas Jet Diffusion Flames," Proceedings of the Thirteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1970, pp. 821-829.

[8]Cochran, T.H., (ed.), "Combustion Experiments in a Zero-Gravity Laboratory," Progress in Astronautics and Aeronautics, Vol. 73, American Institute of Aeronautics and Astronautics, Inc., NY, 1981.

[9]Altenkirch, R.A., Berlad, A.L., DeWitt, K., Hoffman, J., Levine, R.S., Ostrach, S., Summerfield, M.A., and Williams, F.A., "Definition

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of Experiment Requirements for a Spacelab Combustion Facility," USRA Report On NASA Contract NAS3-22651, 1982.

[10]Lavid, M. and Berlad, A.L., "Gravitational Effects on Chemically Reacting Boundary Layer Flows Over a Horizontal Flat Plate," Proceedings of the Sixteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1976, pp. 1557-1568.

[11]Yang, C.H. and Berlad, A.L., "On Kinetics and Kinetic Oscillations in Carbon Monoxide Oxidation," Transaction (I) of the Faraday Society, Vol. 70, 1974, pp. 1661-1675.

[12]Strehlow, R.A. and Reuss, D.L., "Effect of A Zero-G Environment on Flammability Limits as Determined Using a Standard Flammability Tube Apparatus," NASA Report 3259, 1980.

[13]Williams, F.A., "Droplet Burning at Zero-G," NASA CR-159531, 1980.

[14]Summerfield, M. and Messina, N., "Smoldering Combustion in Porous Fuels," NASA CR-159528, 1979.

[15]Kanury, A.M., "Liquid Pool Burning," NASA CR-159642, 1979.

[16]Berlad, A.L., "Thermokinetics and Combustion Phenomena in Nonflowing Gaseous Systems: An Invited Review, "Combustion and Flame, Vol. 21, 1973, pp. 275-288.

[17]Williams, F.A., "Ignition and Burning of Single Liquid Droplets," Proceedings of the 35th IAF Congress, Paper IAF-84-152, 1984. Also, Acta Astronautica, 1985, in press.

[18]Ronney, P.D., "Effect of Gravity on Halogenated Hydrocarbon Flame Retardant Effectiveness," Proceedings of the 35th IAF Congress, Paper IAF-84-156, 1984. Also, Acta Astronautica, 1985, in press.

[19]Berlad, A.L. and Joshi, N.D., "Gravitational Effects On the Extinction Conditions for Premixed Flames, Proceedings of the 35th IAF Congress, Paper IAF 84-151, 1984. Also, Acta Astronautica, 1985, in press.

[20]Vedha-Nayagam and Altenkirch, R.A., "Gravitational Effects On Flame-Spreading Over Thick Solid Surfaces," Proceedings of the 35th IAF Congress, Paper IAF-84-154, 1984. Also, Acta Astronautica, 1986, in press.

[21]Krishna, C.R. and Berlad, A.L., "A Model for Dust Cloud Autoignition", Combustion and Flame, Vol. 37, 1980, pp. 207-210.

[22]Berlad, A.L. "Combustion of Particle Clouds," Progress in Astronautics and Aeronautics, Vol. 73, 1981, pp. 91-127.

[23]Hertzberg, M.H., Cashdollar, K.L., and Lazzara, C.P., "The Limits of Flammability of Pulverized Coals and Other Dusts," Proceedings of the Eighteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1981, pp. 717-729.

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AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[24]Kinbara, T., Endo, H., and Sega, S., "Downward Propagation of Smoldering Combustion Through Solid Materials," Proceedings of the Eleventh Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1967, pp. 525-531.

[25]Mutoh, N., Hirano, T., and Akita, K., "Experimental Study of Radiative Ignition of PMMA," Proceedings of the Seventeenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1978, pp. 1183-1190.

[26]Niioka, T. and Williams, F.A., "Relationship Between Theory and Experiment For Radiant Ignition of Solids," Proceedings of the Seventeenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1978, pp. 1163-1171.

[27]Sirignano, W. and Glassman, I., "Flame Spreading Above Liquid Fuels: Surface-Tension-Driven Flows," Combustion Science & Technology, Vol. 1, 1969, pp. 307-312.

[28]Linan, A., "The Asymptotic Structure of Counterflow Diffusion Flames for Large Activation Energies," Acta Astronautica, Vol. 1, 1974, pp. 1007-1039.

[29]Saitoh, S. and Otsuka, Y., Combustion Science and Technology, Vol. 12, 1976, pp. 135-146.

[30]Seshadri, K., "The Asymptotic Structure of a Counterflow Premixed Flame for Large Activation Energies," (Int. J. Eng. Sci., Vol. 21, 1983, pp. 103-111.

[31]Seshadri K. and Puri, I., private communication.

[32]McCaffry, B.J. and Berlad, A.L., "Some Observations on the Oscillatory Behavior of Carbon Monoxide Oxidation," Combustion and Flame, Vol. 26, 1976, pp. 77-83.

[33]Gray, P., Jones, D.T., and MacKinven, R. "Thermal Effects Accompanying Spontaneous Ignition in Gases," Proc. Roy. Soc. London, Vol. A325, 1971, pp. 175-176.

[34]Yang, C.H. and Gray, B.F., "The Determination of Explosion Limits From a Unified Thermal and Chain Theory," Proceedings of the Eleventh Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1967, pp. 1099-1106.

[35]Destriau, M. and Heleschewitz, H., "Heterogeneous Processes in The Combustion of Gaseous Mixtures," Proceedings of the Eleventh Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1967, pp. 1075-1079.

[36]Howson, A.C. and Simmons, R.F., "The Kinetics of the Thermal Reaction Between Hydrogen and Oxygen in Barium Bromide-Coated Vessels," Proceedings of the Eleventh Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1967, pp. 1081-1089.

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AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[37]Ishihama, W. and Enomoto, H., "New Experimental Method for Studies of Dust Explosions," Combustion and Flame, Vol. 21, 1973, pp. 177-186.

[38]Nagy, J., Dorsett, H.G., and Cooper, A.R., "Explosibility of Carbonaceous Dusts," U.S. Bureau of Mines Report RI-6597, 1965.

[39]Gray, P., Griffiths, J.F., and Mould, R.J., "Thermokinetic Oscillations Accompanying Propane Oxidation," Faraday Symposium of The Chemical Society, Vol. 9, 1974, pp. 103-113.

[40]Yang, C.H. and Gray, B.F., "On the Slow Oxidation of Hydrocarbon and Cool Flames," J. Phys. Chem., Vol. 73, 1969, pp. 3395-3406.

[41]Oran, E.S. and Boris, J.P., "Detailed Modeling of Combustion Systems," Prog. Energy Combustion Science, Vol. 7, 1981, pp. 1-72.

[42]Berlad, A.L., Jaung, R., and Pratt, W.T., "Electric Cable Insulation Pyrolysis and Ignition Resulting From Potential Hydrogen Burn Scenarios For Nuclear Containment Buildings," Proceedings of the Second International Conference on Impact of Hydrogen on Water Reactor Safety, 1982, pp. 1197-1212.

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Comments on Combustion

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Many if not most combustion systems of interest involve the gaseous oxidizer and a gaseous or condensed-phase fuel. For the gaseous oxidizer, naturally induced flows occur when there is a difference between the gravitational body force and the pressure force. These flows can be viewed as being due to density differences in the presence of gravity. In many situations in which the fuel and an ambient oxidizer initially are unmixed (diffusion flames), the flow serves to aid the supply of oxidizer to the flame and the removal of products from the flame. Gas-phase temperatures can range from the adiabatic-stoichiometric flame temperature (typically around 2000-2500 K for hydrocarbons burning in air) to the ambient temperature (usually around 300 K). Such temperature differences result in density differences that are large compared with what normally is encountered in most natural convection situations, giving rise to relatively large velocities.

If liquid phases (e.g., liquid fuels) are present, internal circulation within the liquid due to gravity is possible. It would appear, though, that buoyancy-induced liquid-phase flows are of lesser importance than those induced in the gas. Maximum temperatures, limited by the boiling point, are substantially lower than those quoted above, and liquid densities are not as sensitive to temperature as gas densities. Sirignano concludes that in flame spreading over a pool of liquid fuel, the dominant mechanism for generating liquid-phase flows, which is actually the mechanism responsible for establishing the observed spread rate, is that of forces generated because of surface-tension gradients.[1] Buoyancy-driven liquid flows are generally only important for rather large-scale fires.[1]

Berlad, then, correctly focuses on the effects of gravity on the gas-phase flow field and the effect this flow

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field or its possible absence at reduced gravity has on the combustion process. Many combustion theories ignore the effects of gravity and the induced flow, even in situations in which it is known to be potentially important, to allow the resulting problem to be mathematically tractable. Results from such theories are compared with Earth-bound experiments in which gravity is present, and it may not be clear the extent to which discrepancies between theory and experiment are due to the presence of gravity. Particle (liquid or solid) combustion in a quiescent oxidizer falls into this category of combustion problems.

The classical theory of droplet combustion, in which the effects of buoyancy are neglected, has been around for some time.[2] In the absence of gravity and any forced flow, the diffusion flame surrounding the droplet is spherically symmetric. The momentum equation reduces to a statement that the pressure is constant, and the resulting linear problem for the species, temperature, and flow field and burning rate can be solved easily, assuming thermodynamic equilibrium at the liquid-gas interface and that gas-phase chemical reactions proceed at an infinite rate. The theory can be tested only at a low Grashof number (the ratio of a buoyancy force to a viscous force),[3] which can be achieved by using small droplets or performing experiments at low pressures. But small droplets are affected by their support, and they are difficult to study in free fall.[4] In addition, a reduction in droplet size or oxidizer pressure may cause a reduction in the Damkohler number in the gas (the ratio of a flame-zone residence time to a flame-zone chemical reaction time), resulting in finite-rate, gas-phase chemistry becoming important, which violates one of the assumptions on which the theory is based.

Some progress has been made in including the effects of buoyancy and finite-rate, gas-phase chemistry in droplet-burning theory.[5,6] For small particles such as those encountered in liquid sprays, droplet extinction under spherically symmetric conditions at small diameters can be used to determine kinetic constants of a chemical reaction of assumed order. Pressure changes also may allow the order of the reaction near extinction to be determined. Such experimental results are best achieved under reduced-gravity conditions in which spherical symmetry and single, free droplets can be obtained.[4,6]

Certain combustion experiments are not only affected by the flows induced by buoyancy but also are nearly impossible to carry out on Earth. These types of experiments usually fall into one of two categories: those for which the initial condition cannot be set up at normal

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gravity, or those low-gravity experiments for which sufficient experimental time cannot be generated by Earth-based experimental facilities such as drop towers. Flame propagation through a uniform cloud of combustible particulates falls into the former category, whereas the free-droplet combustion experiment falls into the latter.[4]

Another combustion problem mentioned by Berlad that is difficult to study under low-gravity conditions in Earth-based laboratories is that of flame spreading over a solid fuel in the absence of forced or naturally induced oxidizer flow. Understanding the physics of this process is important to the fire-safety aspects of space travel, particularly for future manned space missions that are apt to be over prolonged periods of time.

Currently, flame spreading (Fig. 1) is best understood in the presence of either a forced or naturally induced flow, a situation that is somewhat opposite to that of droplet combustion.[8-11] This point is not clearly established by Berlad. Certain combustion problems are better understood in the presence of buoyancy than in its absence; flame spreading appears to be one of them. Flames spread over a solid fuel by transferring heat forward to bring the unburnt fuel up to a pyrolysis temperature where it is capable of vaporizing to support the gas-phase flame. Forward heat transfer is essential in almost all flame-spread theories. Downward flame spreading over thin fuels (paper) and thick fuels (polymethylmethacrylate

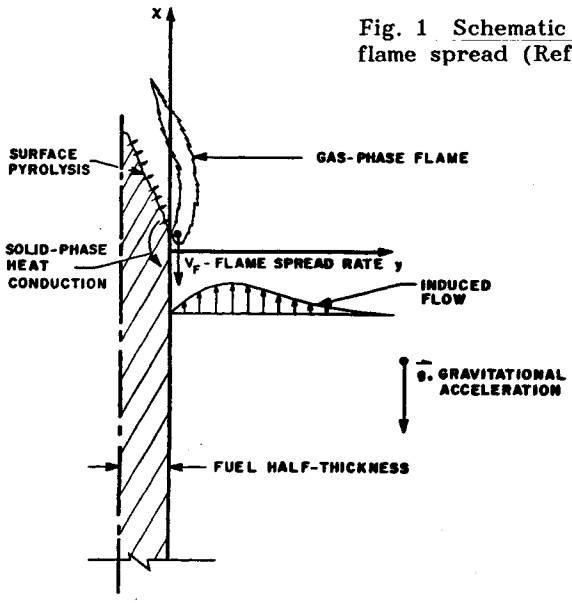

Fig. 1 Schematic illustration of downward flame spread (Ref. 7).

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or Plexiglas) has been correlated using a dimensionless spread rate that is a measure of the forward heat transfer and a Damkohler number, again a ratio of the flame-zone residence time to the flame-zone chemical reaction time.[10,11] For infinite Damkohler number, the dimensionless spread rate is unity; as the Damkohler number is reduced, a minimum value is reached, below which extinction is reached.

The flame-spread correlations mentioned above, although containing the acceleration of gravity, fail as the gravity level reaches that obtained on a spacecraft. Indeed, as gravity vanishes, both the Damkohler number and the dimensionless spread rate, at least for a thick fuel, approach infinity for all experimental conditions with finite oxidizer concentration. This is because the characteristic fluid velocity and length scales are based on buoyancy being dominant in establishing the gas-phase flow. At reduced gravity, the interfacial velocity due to pyrolysis becomes dominant and is responsible for establishing the gas-phase flow. No theories for this configuration are available, and the amount of data available is limited. In addition, drop-tower experiments suffer from, under many conditions, an insufficient time in which to achieve a steady spread.[12]

One theme that appears above, but that is not emphasized enough by Berlad, is that it is in fact dimensionless parameters that are of primary concern rather than the dimensional parameter gravitational acceleration. Often, "reduced"-gravity experimentation can be performed at normal gravity by carefully choosing the values of other dimensional parameters. As discussed in Ref. 13, for flame spread down Plexiglas fuel beds, spread rates down to 10^{-3} g (with g measured in the units of Earth's normal acceleration) were predicted from elevated-gravity experiments and the dimensionless correlations presented in Ref. 11. The analysis presented there, which compared favorably with experiments for gravity levels below that of Earth (see Fig. 2), is a large Grashof number theory. One cannot hold then that by carrying out combustion experiments at gravity levels below that of Earth, one necessarily will learn something new. Experimental conditions, including gravity level, must be chosen wisely using whatever analysis is available.

Berlad's chapter states the essential reasons why combustion experimentation under low-gravity conditions is likely to provide new insights into certain combustion phenomena. They are summarized as follows:

- Many combustion theories are based on the neglect of the effects of gravity and cannot be adequately

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tested in Earth-based laboratories (e.g., the autoignition phenomena).

- o Low-gravity combustion experiments can be used to elucidate how buoyancy-induced flows affect combustion processes for those processes in which the effect is not clearly understood (e.g., flammability limits in premixed gases).
- o Low-gravity conditions allow certain combustion experiments to be established that are difficult if not impossible to set up on Earth (e.g., particle-cloud combustion).

It is important to attempt to analyze combustion problems in terms of dimensionless parameters where the scales of measure are internal. More physical insight is apt to be had than when dimensional parameters are used. Although Earth-based experimental laboratories are capable of answering some of the questions concerning combustion under low-gravity conditions, the performance of many experiments requires time periods that necessitate the use of space-based laboratories.

Berlad presents a list of combustion phenomena that would be better understood if experiments on them were carried out under low-gravity conditions. Although study of any of these phenomena is apt to provide us with some additional insight, some seem to be more important than others. Studies of premixed flame propagation and flam-

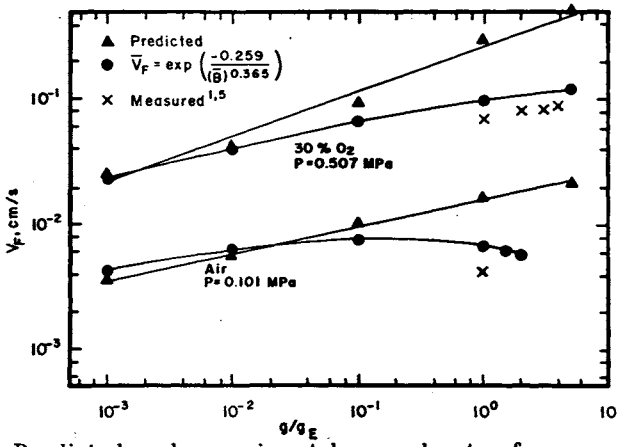

Fig. 2 Predicted and experimental spread rates for spread down a semi-infinitely thick PMMA fuel bed as a function of gravitational acceleration. (Reprinted with permission from Acta Astronautica, Vol. 12, Vedha-Nayagan, M. and Altenkirch, R.A., "Gravitational Effects on Fames Spreading over Thick Solid Surfaces," copyright 1985, Pergamon Press, Ltd. [Ref. 13].)

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mability limits would be particularly helpful in providing information on the nature of flammability limits, a phenomenon that is less than well understood. In addition, most appropriate are phenomena in which exact theoretical descriptions can be developed and low-gravity experiments used to deduce results nearly impossible to obtain on Earth. Droplet burning would fall into this latter category. These two combustion phenomena, flammability limits and droplet burning, have been singled out by Berlad as two that would be particularly fruitful to study at low gravity, the first phenomenon because little is known of it and the second because certain aspects of it are well-understood.

References

[1]Sirignano, W.A., "A Critical Discussion of Theories of Flame Spread Across Solid and Liquid Fuels," Comb. Sci. Technol., Vol. 6, 1972, pp. 95-105.

[2]Williams, F.A., Combustion Theory, Addison-Wesley, Reading, MA, 1965.

[3]Law, C.K. and Williams, F.A., "Kinetics and Convection in the Combustion of Alkane Droplets," Comb. Flame, Vol. 19, 1972, pp. 393-405.

[4]Williams, F.A., "Ignition and Burning of Single Liquid Droplets," Acta Astronautica, in press.

[5]Fernandez-Pello, A.C. and Law, C.K., "A Theory for the Free-Convective Burning of a Condensed Fuel Particle," Comb. Flame, Vol. 44, 1982, pp. 97-112.

[6]Wu, X., Law, C.K., and Fernandez-Pello, A.C., "A Unified Criterion for the Convective Extinction of Fuel Particles," Comb. Flame, Vol. 44, 1982, pp. 113-124.

[7]Vedha-Nayagam, M., "Flame Spreading in Backward Boundary Layers," Ph.D. Thesis, University of Kentucky, Lexington, KY,1985.

[8]Fernandez-Pello, A.C. and Hirano, T., "Controlling Mechanisms of Flame Spread," Comb. Sci. Technol., Vol. 32, 1983, pp. 1-31.

[9]Wichman, I.S., "A Model Describing the Influence of Finite-Rate Gas-Phase Chemistry on Rates of Flame Spread Over Solid Combustibles," Comb. Sci. Technol., Vol. 40, 1984, pp. 233-255.

[10]Altenkirch, R.A., Eichhorn, R., and Shang, P.C., "Buoyancy Effects on Flames Spreading Down Thermally Thin Fuels," Comb. Flame, Vol. 37, 1980, pp. 71-83.

[11]Altenkirch, R.A., Eichhorn, R., and Rizvi, A.R., "Correlating Downward Flame Spread Rates for Thick Fuel Beds," Comb. Sci. Technol., Vol 32, 1983, pp. 49-66.

[12]Andracchio, C.R. and Cochran, T.H., "Gravity Effects on Flame Spreading over Solid Surfaces," NASA TN D-8828, 1976.

[13]Vedha-Nayagam, M. and Altenkirch, R.A., "Gravitational Effects on Flames Spreading Over Thick Solid Surfaces," Acta Astronautica, Vol. 12, 1985, pp. 565-572.

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Fluid Mechanics and Fluid Physics in a Low-Gravity Environment

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Introduction

Routine use of the low-gravity environment for research in fluid mechanics has not been rapidly accepted. Not the smallest barrier has been a belief by some scientists and engineers that experiments in space would be unthinkably expensive and complicated. This belief translates into a position that to justify the conduct of an experiment in space, one would first have to establish that the experiment could not, under any circumstances, be done on Earth. Early meetings on physics and chemistry experiments in space often were paralyzed by this viewpoint. Yet, some people argued that thinking about using the low-gravity environment should be considered no more strange than using any other scientific tool or facility, such as, in the 1960s, working at temperatures of 1 millikelvin or having supercomputing facilities routinely available to university researchers. These examples were simply additional long-range visions of a few far-seeing people. But they are steadily gaining acceptance and becoming used routinely.

Once one proceeds beyond the psychological barriers to research in space, one's attention focuses instead on how those fluid mechanical effects accepted on Earth might be altered if gravity were removed or, going one step further, if accelerations were obtained in a controlled manner. With this more general idea in mind, it is argued by specific examples that there are many phenomena in fluid mechanics for which the motions caused by gravity 1)

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complicate the interpretation of experimental results, 2) mask the effects in question, 3) make good theories intractable, 4) limit the length scales in experiments, and/or 5) limit accessible regions of parameter space.

These points are discussed below. This discussion is not intended to develop specific experiments that can be carried out but to describe broadly the type of physical environment low gravity, and indeed controlled gravity, makes possible. The viewpoint herein is that fluid systems encompass an enormous range of phenomena in which the effects of gravitational forces are significant and that may, because of the complications listed above, be considered prime candidates for experimentation in a low-gravity environment.

Although cited examples span a broad class of fluid phenomena, there are some recurrent themes that lead to certain general scientific issues and questions. These revolve around the emerging study of nonlinear systems, as typified by strongly nonlinear turbulent flows, systems in which free boundaries occur and in which complicated patterns can form, and problems in which instabilities and postinstability behavior are not simple and cannot be inferred from physical intuition and limited theoretical knowledge. Because most examples below involve nonlinear systems, another expression of the same set of issues might take the form of a series of questions involving the nature of bifurcations, limit points, and possible "generic" routes to temporal or spatial turbulence, and whether those strongly nonlinear systems give behaviors that have a chaotic or fractal nature. Recent work on mathematical models and nonlinear dynamical systems has indicated a plethora of routes to chaotic behavior. At this stage of development, then, few if any general statements can be made that apply equally to all systems. Just as there are many fluid systems in which these issues may be probed profitably in the normal gravitational field of 1 g without the complications listed above, there are a number of systems--typically multiphase systems, interfacial problems, or systems near critical points--in which the presence of gravity constitutes a significant perturbation.

Another important consideration in this discussion is the extent to which theoretical and numerical studies can answer such questions, especially with the advent of supercomputers. Accordingly, examples have been chosen in which, although the basic physical laws governing the phenomenon may be well-established, the behaviors are time-dependent, three-dimensional, or both, and involve such a wide spectrum of length and time scales as to render them essentially uncomputable, at least in the near term.

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Cases in Which Gravity Complicates the Interpretation of Experimental Results

Dendritic Growth

The growth of crystals is an important technological area. It is also of interest, however, as a member of a class of pattern-formation problems in physics. For some of these pattern-formation problems (e.g., viscous fingering and diffusion-limited aggregation of colloids), gravity is not a significant complication. The patterns formed by dendritic growth of crystals, however, are different. Dendritic growth is characterized by the morphological instability of a growing crystal. This instability leads to side branching, and those side branches may undergo subsequent secondary instabilities and repeated branching. The geometrical properties of the resulting dendritic structure are of great interest; in particular the volume-filling properties may have a fractal character. Questions of the mechanisms of such branching instabilities are also of interest, as there is some evidence that they reflect crystal anisotropies at the molecular level. Glicksman et al. have shown such tip instabilities and repeated branchings in a set of beautiful experiments.[1,2]

Note, however, that crystal growth is essentially a nonisothermal process, and the entire dendrite-melt system is subject to a nonuniform energy source due to latent heat release. Thus, at some scale, buoyancy-driven convection influences the transport of material to the crystal surface, thus affecting the growth rates and growth properties in a way that depends on the orientation of the boundary relative to gravity. Indeed, Glicksman et al. have shown substantial differences in surface morphology and branching structure for dendrites grown parallel and antiparallel to gravity, with those antiparallel to gravity exhibiting substantially stunted growth.[1,2] Because crystal growth involves a free boundary that occurs at all orientations relative to gravity and because the length scale of the pattern is increasing continually, these convective effects complicate the measurement and inference of the asymptotic state of dendritic growth at long times and large length scales.

Mechanics of Granular Media

Consider the material behavior of cohesionless granular materials such as sand, flocs, and powders. These materials are very weak compared with other engineering materials and therefore have low failure stresses. Post-

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failure behavior is important in a variety of scientific and engineering applications, including chemical processing of catalytic powders, earthquake engineering, geophysical catastrophes (e.g., eruptions and landslides). The presence of gravity represents a nearly insurmountable obstacle to the measurement of failure criteria, failure mode, and microscopic failure mechanisms on the one hand, and postfailure behavior on the other. This is so because in a sample of sufficient size that continuum properties can be measured, the axial stress due to gravity causes a stress gradient in the sample. This in turn leads to an inhomogeneous material, because some portions are postfailure and some prefailure.

A Physics and Chemistry Experiments (PACE) project, under the direction of Professor S. Sture, University of Colorado, and Dr. N. Costes, Marshall Space Flight Center, is under development to study these issues. The objectives of the experiment are to make measurements of the stress-deformation behavior of these materials under low confining stresses. Conventional triaxial compression tests with continuous measurement of load and strain are planned. Furthermore, local "microscopic" photographic measurements of the motion of individual particles and grains will give insight into the grain-level mechanisms of failure. These results will be useful for formulating and testing nonlinear constitutive equations for such materials.

Cases in Which Gravity Masks Effects of Interest

There are circumstances in which removal of gravity allows one to more efficiently study phenomena that are present, but masked, in the normal gravitational environment of 1 g. Note that reduction of gravity often results in a reduction or removal of a characteristic length or time scale, so that many possible and popular examples in this category--for example, motion of a contact line at the junction between two fluids and a solid, meniscus shapes in static and dynamic conditions, and wetting and spreading of droplets--also can be considered as providing examples of cases in which gravity limits accessible length scales.

Moving to smaller scale systems often has the same dynamical effect as reducing gravity, as discussed below. However, there are some examples for which this is not true, specifically those examples addressed by Professor John Hart (see Chapter 8B). To study geophysical flows in spherical shells in the examples cited by Hart, a purely radial orientation of the gravity vector is essential and obviously cannot be accomplished in a terrestrial setting.

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In his chapter, Hart discusses the details of how this is accomplished in a low-gravity environment by using a dielectric fluid.

Cases in Which Gravity Makes Good Theories Intractable

Perhaps the most compelling example of this category is that of combustion. (Combustion is the topic of Chapter 7A by Professor A. L. Berlad.)

Chemically reacting systems are influenced by convection, diffusion, rates of chemical reaction, and phenomena associated with multicomponent fluid systems (e.g., thermal diffusion). They are governed by a set of convective-diffusion-reaction equations of the form

$$Dc_i/Dt = 1/Pe_{D_i} \nabla^2 c_i - D\, R_i(c_1, c_2, \ldots, T) \qquad i = 1, 2, \ldots N \tag{1}$$

and

$$DT/Dt = 1/Pe\, \nabla^2 T + D \sum \Delta H_i R_i \tag{2}$$

Here Pe, Pe_{Di} are the Peclet numbers for heat and species transfer, respectively; D is a dimensionless characteristic chemical reaction rate (Damkohler number); and ΔH_i are dimensionless energies of reaction. The reaction rate terms, R_i, are often highly nonlinear, especially with respect to their temperature dependence, and therefore a rich variety of bifurcation and instability phenomena is possible. These equations must be augmented by the usual equations describing the nonisothermal fluid mechanics of the mixture.

One of the great challenges in the field of combustion is to attempt to be faithful to both the complicated chemistry and the fluid flow. This is often impossible, but progress can be made in cases in which the flow field is not too complicated. The minimization of buoyant convection admits the possibility that the flow field may be considerably simpler than would otherwise be the case.

Cases in Which Gravity Limits the Length Scales of Experiments

Combined Buoyancy and Surface-Tension-Driven Convection

Surface-tension-driven phenomena arise whenever a free surface of surface tensions interacts with a field (temperature, T; magnetic field, B; electric field, E; and so

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on) that influences surface tension. The case of thermocapillary convection has been reviewed in depth by Ostrach.[3] Consider the two prototype problems sketched in Fig. 1: a) involves a stability problem, with a threshold temperature difference ΔT required for convection; b) involves convection no matter how small ΔT. In a), the problem is governed by the following dimensionless groups[4] and thermal boundary conditions at all surfaces. In b), similar definitions hold with the exception of the capillary number (C_a).[3] For other fields, such as electrohydrodynamics, similar groups arise. Gravity enters the problem through the Rayleigh number (R_a, buoyancy-driven effects within the fluid) and the Bond number (G, density differences $\Delta\rho$ at the interface). C_a is a measure of interfacial deflection due to convection. (See Table 1.)

Minimizing Buoyancy-Driven Effects. To do an experiment that is essentially dominated by surface-tension-

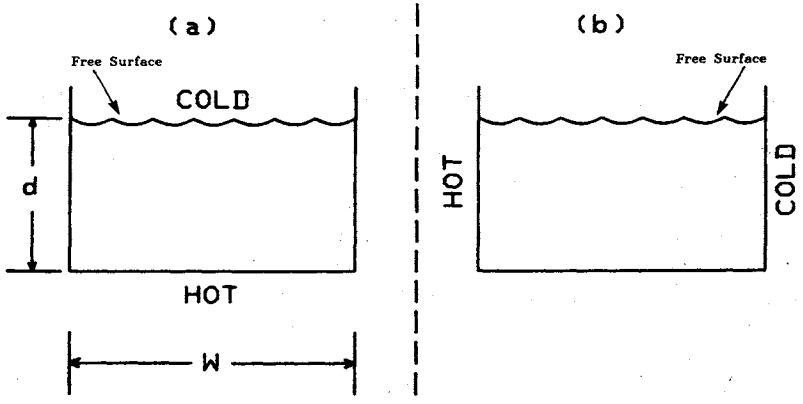

Fig. 1 Two cases of convection in a layer of fluid of depth d and width W where surface tension may be of importance. The scalloped line marks the location of the free surface. Cases a) and b) are discussed in the text.

Table 1 Dimensionless groups governing convection

Dimensionless Group	Definition
Rayleigh number	$R_a = g\alpha\Delta T d^3/\nu\kappa$
Marangoni number	$M_a = (-\partial\sigma/\partial T)\Delta T d/\mu\kappa$
Capillary number	$C_a = (\mu\kappa/\sigma d)$
Contact angle	$= \gamma$
Prandtl number	$P = \nu/\kappa$
Bond number	$G = \Delta\rho g d^2/\sigma$
Aspect ratio	$A = d/w$

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driven convection far into the nonlinear regime at high Marangoni numbers (M_a), the following conditions must hold

$$M_a >> R_a \tag{3}$$

or

$$d^2 << (-\partial\sigma/\partial T)/(\partial\rho/\partial T)g \tag{4}$$

when using typical values of $-(\partial\sigma/\partial T) = 7 \times 10^{-2}$ dynes/cm-K; $-(\partial\rho/\partial T) = 1 \times 10^{-3}$ g/cm^{3}K; $g \simeq 10^3$ cm/s^2; and $d << 3$ mm.

This fact is well-known: for most fluids one must go to submillimeter length scales before minimizing (but not completely eliminating) buoyancy effects. Such experiments in thin layers have been conducted[5-7] but with some degree of difficulty. Furthermore, most measurements at such length scales are limited to global properties (e.g., surface average temperature and average heat flux). If field information (e.g., obtained by velocimetry or thermal profiling) is desired, it cannot be obtained working at such small length scales. A PACE project (S. Ostrach, Principal Investigator) is under development in an attempt to measure such field information in domains whose characteristic length is of order centimeters, not millimeters. Low-gravity studies of surface-tension-driven flows thus present opportunities but also present complications regarding the effect of gravity-jitter on interfacial stability and integrity.

Minimizing Free-Surface Deflections. Free-surface deflections as a result of convection make the posed problem a free-boundary one. Challenging numerical difficulties arise if such free-boundary problems are treated in generality. However, for most fluids

$$C_a = (\mu\kappa/d\sigma) \sim 10^{-4}/d \tag{5}$$

where experimenters use cgs units. Thus C_a is small for any reasonable length, d[3,8] and steady flows may be computed for comparison with experiment by domain perturbation. However, instability modes may be linked intimately with free-surface deformability and three-dimensional flows, as suggested by Smith and Davis.[9,10] As a result, in experiments involving finite amplitude, traveling waves are the only practical way of probing nonlinear instabilities: computations of such three-dimensional, time-dependent, free-boundary problems at high Marangoni numbers are simply too difficult.

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Minimizing the Effect of Gravity on Free-Surface Shapes. To minimize the effect of gravity, we must have the Bond number, G, much less than unity. For most fluids in 1 g

$$G \sim (1)(10^3)(d^2)/50 \sim 20\, d^2 \tag{6}$$

Again $G << 1$ implies $d^2 << .05\ cm^2$, or $d << 2$ mm, that is, length scales of the order of millimeters.

Mechanics of Suspensions

The problems of effective rheological properties of suspensions date from A. Einstein's thesis[11]; because of their industrial and technological importance (e.g., slurries, separations, colloidal dispersions, flocculation, and blood flow), they have been studied intensively for the last 80 years. One quantity of interest is the effective shear viscosity μ of a suspension of neutrally buoyant particles, normalized by the viscosity μ_o of the suspending fluid. Einstein showed that for spheres

$$\mu/\mu_o = 1 + \frac{5}{2}\phi \qquad \phi << 1 \tag{7}$$

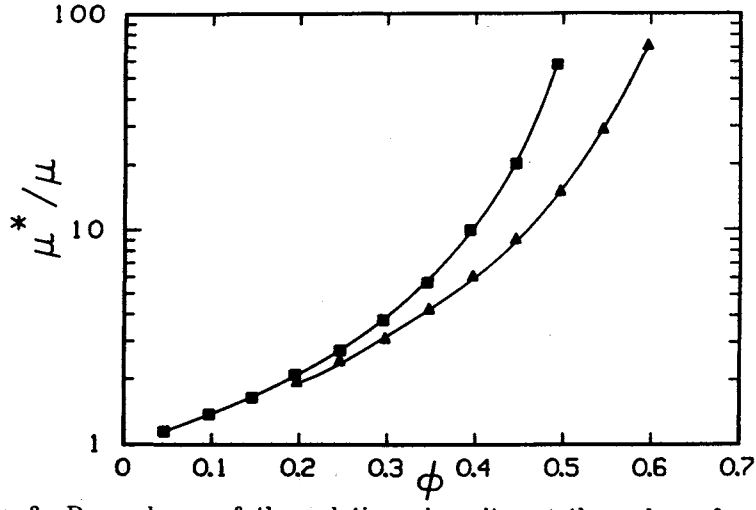

Fig. 2 Dependence of the relative viscosity on the volume fraction of spheres ϕ. Different symbols indicate the degree of scatter from apparatus to apparatus.

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where ϕ is the volume fraction of spheres. Data on such systems show a typical behavior with much scatter at high concentrations (Fig. 2). There is still no convincing theoretical description of such behavior. More complicated systems (anisotropic particles, emulsions whose dispersed phase can distort, polymer molecules whose conformation can change dramatically, and colloidal systems influenced by electrostatic and London forces) are even more challenging.

Some years ago, Frankel and Acrivos[12] introduced an ad hoc model that suggested that μ/μ_o diverges at a critical concentration, ϕ_c, above which the suspension can no longer be sheared without dilation. They further suggested that

$$\mu/\mu_o \sim 1/(1 - \phi/\phi_c)^{1/3} \tag{8}$$

and that the "critical exponent" was in reasonable agreement with experiments. Because of the scatter in the data, however, both the leading constant and ϕ_c varied unpredictably. Very recently, Bossis and Brady[13,14] performed large-scale numerical simulations of sheared, two-dimensional layers of spheres at high concentrations. The "exact" calculation of such a two-dimensional problem required substantial time on a Cray supercomputer; an exact three-dimensional calculation is out of the question. These calculations have shown that effective properties do diverge and that this divergence is a result of the formulation of large but transient clusters of particles with large components of relative velocity along their lines of centers. The divergence is then associated with these clusters reaching a percolation threshold that causes their correlation length to diverge. As one approaches ϕ_c, the finite size of the apparatus comes into play, with the accompanying variation from apparatus to apparatus. To experimentally probe the region near ϕ_c, it is necessary to use a large apparatus, but no system is perfectly neutrally buoyant. Small mismatches in density due to materials used, small temperature gradients, and so forth, will have larger effects as sample size increases.

A measure of the effect variations in density would have on such a suspension is given by a sedimentation Grashof number

$$G_r = g\Delta\rho d^3/\rho\nu^2 \tag{9}$$

Suppose the density variation in $\Delta\rho/\rho$ is controlled to 1% and the fluid is a viscous solvent with $\nu \sim 1$ cm^2/s. Then

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the requirement that $G_r \ll 1$ leads to

$$d^3 \ll \rho\nu^2/\Delta\rho g \tag{10}$$

Then in 1 g, d << 5 mm, which is far too small to probe for percolation clusters near ϕ_c. In practice, greater control of density is possible, but working with a more viscous solvent presents mechanical problems with the high effective viscosities encountered near ϕ_c. Obviously, working with smaller g levels allows one to increase d without encountering significant sedimentation problems and thus to conduct reliable experiments closer to ϕ_c.

Liquid ^{4}He

The lambda transition in liquid helium (He) is the line on the diagram of state (see Fig. 3) that separates normal He-I from He-II, which exhibits superfluidity. The figure shows that this line has a negative slope, which fundamentally limits the closeness of approach one can obtain on Earth to T_λ. It is desirable to get data closer and closer to a phase transition because the predicted properties of phase transitions show some sample-independent features sufficiently close to the transition. In particular, the properties of liquid He are thought to be "universal," that is, independent of pressure as one approaches the transition.

Figure 3 shows the essence of the difficulty. On Earth the hydrostatic head of liquid He in the sample

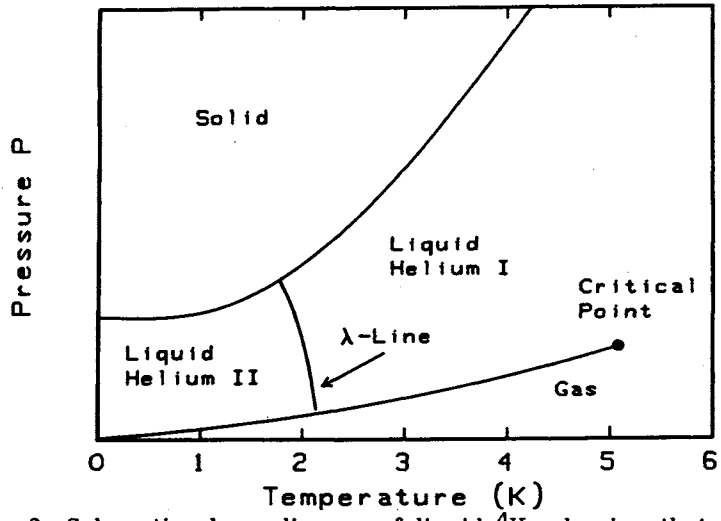

Fig. 3 Schematic phase diagram of liquid ^{4}He showing that the λ-line connecting He-I and He-II has a negative slope.

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gives a hydrostatic pressure $P = \rho gh$, where h is the height of the fluid. When gravity is present and one is sufficiently near T_λ, the top of the test-sample cell will be in He-II and the bottom in He-I, the transition line being somewhere in the liquid in the container. Moreover, the properties of the fluid will be smeared out in the container instead of belonging to the temperature and pressure of interest. More complicating still is the existence of size effects; that is, there is a coherence length, which is growing large and, indeed, diverging at the lambda transition. On Earth the samples are made ever smaller to avoid gravitational smearing when good science requires that they be made larger. Thus the length scale of these experiments is limited severely by the effects of gravity. (See Chapter 2A by Dr. John Lipa.)

Cases in Which Gravity Limits Regions of Parameter Space

Interfacial Shapes

The mathematical theory of solutions to the equations governing isothermal, steady interfacial shapes without gravity (the Young-Laplace equation) indicates that there are combinations of contact angles and container geometries for which steady, single-valued solutions do not exist. This theory raises the following questions: 1) do real fluids exhibit this loss of single-valued shapes, and, if so, 2) what configurations will such fluids take when the critical conditions are exceeded? Although it is possible to explore these issues partially by using either neutrally buoyant fluid pairs or drop towers, the range of contact angles that can be studied and/or the duration of the experiments is severely limited. A low-gravity environment could provide the capability of investigating a wide range of contact angles and container shapes over relatively long periods of time.

Let Ω be the arbitrary cross section of a cylinder (Fig. 4). Let $\sum$ be the boundary of Ω, $Z = h(x,y)$ be the interfacial location, and γ be the contact angle. The Young-Laplace equation of capillary statics is

$$\nabla \cdot (\underline{H}) = \text{const in } \Omega \qquad (11)$$

$$\underline{H} \cdot \underline{n} = \cos \gamma \quad \text{on } \sum$$

where $\underline{H} = \nabla h/[1 + (\nabla h)^2]^{\frac{1}{2}}$ is the curvature and $\underline{n}$ is the outward normal. For some combinations of $\sum$, Ω, and γ there are no solutions to this equation set (see Concus and Finn[15-17]).

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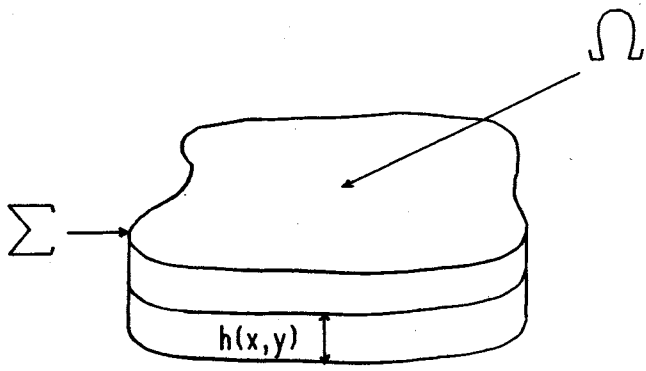

Fig. 4 Cylinder of arbitrary cross-section Ω and boundary ∑; z = h(x,y) specifies the location of the interface.

A PACE experiment (R. Finn, P. Concus, D. Coles, Principal Investigators) is under development to measure interfacial shapes and address the questions raised above.

Parametrically Modulated Systems

Parametric modulation of fluid systems is a relatively new field of research of great intrinsic interest (see, for example, Davis[18]). Parametric modulation of a nonlinear system can be accomplished by introducing an incommensurate frequency or by force-exciting other modes. A nonlinearly forced system with three or more competing modes having a shared bifurcation can exhibit chaos.

One example of a modulated system is the Faraday experiment in which standing waves are observed in a dish of fluid vibrated vertically. Here, of course, the modulation is required to produce the motion under study. One of the interesting features in such experiments is the approach to chaos (see, for example, Keolian et al[19]), but another is the case in which two modes of oscillation are degenerate.[20] On Earth such modulation is limited to small variations of about 1 g. In space these could be done about zero or some adjustable mean gravity, thus greatly expanding the available range of modulation parameters.

Experiments on codimensional two systems are currently of interest. A recent experiment by Ahlers' group studied Bénard convection of ^{3}He-^{4}He mixtures in a porous medium in which two modes are known to be degenerate.[21] Modulation of such a system may produce chaotic behavior in the immediate vicinity of the convective threshold and is likely to be explored in the near future. Gravitational modulation could be a candidate for such an experiment,

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although in the Bénard system the time scales for some arrangements are so large that even in zero mean gravity the required amplitude of modulation might be too large to be realistic.

Other Fluid Systems

Steady thermal convection experiments in Bénard cells are governed by the Rayleigh number defined above. The value of g is, of course, usually fixed, and one varies the fluid properties to achieve various ends, such as Boussinesq or non-Boussinesq properties (see Walden and Ahlers[22]). Allowing g to be a variable may usefully enlarge the available parameter space for such investigations.

A great deal of thought has been given to the behavior of drops and bubbles and the systems they model. Two symposia on this topic have been held.[23,24] One of the topics of the first symposium was the behavior of a rotating mass of fluid constrained by surface tension. This is the famous Plateau experiment in which an attempt was made to minimize the effect of gravity by making a neutrally buoyant drop. A recent review outlines the situation and describes a repeat of Plateau's experiment.[25] Dr. Taylor Wang of the Jet Propulsion Laboratory already has flown a rotating drop experiment on Spacelab 3 and, despite technical difficulties at the beginning of the mission, has observed some beautiful bifurcations.

Generalizations readily can be envisioned: a very important problem is the spin-up of quantum fluids. It should be possible to arrange a revolving superfluid drop with a single quantized vortex line on its axis. It may be possible in a low-gravity system to make neutrally buoyant particles (hydrogen-deuterium mixtures) that could trace the location of such a vortex line in superfluid He. All attempts to do this on Earth have failed, in part because of settling problems in a fluid with such small density (.145 gram/cm^3).

Experiments on surface instabilities such as the breakup of a fluid jet into droplets are limited on Earth because the jet is usually vertical and therefore subject to acceleration in 1 g. The acceleration also changes the diameter of the jet and limits the duration of observation. Low gravity ameliorates these problems: jets and, for that matter, sheets of fluid could be deployed and examined for instabilities without the limitations described above. Thus, the range of parameters available is much enlarged owing to the removal of gravity.

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Conclusions

This chapter has sought to produce a novel classification of experiments on fluid systems that might merit study in a low-gravity or controlled-gravity environment. In any specific case, arguments probably can be made to include the experiments under more than one of the categories above. Whenever possible, the dimensionless groups relevant to the phenomena under study have been listed to allow one to estimate how successful any given arrangement is likely to be. Irrespective of the details, the examples given should demonstrate that fluid dynamics experiments provide an astonishingly wide range of phenomena that would benefit from research in space.

Acknowledgments

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References

[1]Glicksman, M.E., Singh, N.B., and Chopra, M., "Gravitational Effects in Dendritic Growth," Manufacturing in Space, Vol. 11, edited by L. Kops, ASME, New York, 1982, pp. 207-217.

[2]Glicksman, M.E., Singh, N.B., and Chopra, M., "Influence of Diffusion and Convective Transport on Dendritic Growth in Dilute Alloys," Materials Processing in the Reduced Gravity Environment of Space, edited by G. E. Rindone, Elsevier, NY, 1982, pp. 461-465.

[3]Ostrach, S., "Low Gravity Fluid Flows," Ann. Rev. Fluid Mech., Vol. 14, 1982, pp. 313-345.

[4]Davis, S.H. and Homsy, G.M., "Energy Stability Theory for Free-Surface Problems: Buoyancy-Thermocapillary Layers," J. Fluid Mech., Vol. 98, 1980, pp. 527-553.

[5]Kamotani, Y., Ostrach, S., and Vargas, M., "Oscillatory Thermocapillary Convection in a Simulated Floating-Zone Configuration," J. Crystal Growth, Vol. 66, 1984, pp. 83-89.

[6]Preisser, F., Schwabe, D., and Scharmann, A. J., "Steady and Oscillatory Thermocapillary Convection in Liquid Columns With Free Cylindrical Surface," J. Fluid Mech., Vol. 126, 1983, pp. 545-567.

[7]Palmer, H. and Berg, J., "Convective Instability in Liquid Pools Heated From Below," J. Fluid Mech., Vol. 47, 1971, pp. 779-787.

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[8]Scriven, L.E. and Sternling, C., "On Cellular Convection Driven By Surface-Tension Gradients: Effect of Mean Surface Tension and Surface Viscosity," J. Fluid Mech., Vol. 19, 1964, pp. 321-340.

[9]Smith, M. and Davis, S.H., "Instabilities of Dynamic Thermocapillary Liquid Layers. Part I. Convective Instabilities," J. Fluid Mech., Vol. 132, 1983, pp. 119-144.

[10]Smith, M. and Davis, S.H., "Instabilities of Dynamic Thermocapillary Liquid Layers. Part 2. Surface Wave Instabilities," J. Fluid Mech., Vol. 132, 1983, pp. 145-162.

[11]Einstein, A., Ann. Phys., Vol. 19, 1906, pp. 289-306; Vol. 34, 1911: pp. 591-592. See also Investigations on the Theory of Brownian Movement, Dover, New York, 1956.

[12]Frankel, N. and Acrivos, A., "On the Viscosity of a Concentrated Suspension of Solid Spheres," Chem. E. Sc., Vol. 22, 1967, pp. 847-853.

[13]Bossis, G. and Brady, J., "Dynamic Simulation of Sheared Suspensions. I. General Method," J. Chem. Phys., Vol. 80, 1984, pp. 5141-5147.

[14]Bossis, G. and Brady, J., "The Rheology of Concentrated Suspensions of Spheres in Simple Shear Flow by Numerical Simulation," J. Fluid Mech., Vol. 155, 1985, pp. 105-129.

[15]Concus, P. and Finn, R., "On Capillary Free Surfaces in the Absence of Gravity," Acta Math., Vol. 132, 1974, pp. 177-198.

[16]Concus, P. and Finn, R., "A Singular Solution of the Capillary Equation. I. Existence II. Uniqueness," Inventiones Math., Vol. 29, 1975, I pp. 143-148, II pp. 149-159.

[17]Concus, P. and Finn, R., "On the Height of a Capillary Surface," Math Zeit., Vol. 147, 1976, pp. 93-95.

[18]Davis, S.H., "The Stability of Time-Periodic Flows," Annual Review of Fluid Mechanics, Vol. 8, 1976, pp. 57-74.

[19]Keolian, R., Turkevich, L.A., Putterman, S.J., Rudnick, I., and Rudnick, J., "Subharmonic Sequences in the Faraday Experiment: Departures From Period Doubling," Phys. Rev. Letters, Vol. 47, 1981, pp. 1133-1136.

[20]Ciliberto, S. and Gollub, J.P., "Chaotic Mode Competition in Parametrically Forced Surface Waves," submitted to J. Fluid Mech., Vol. 158, 1984, pp. 381-398.

[21]Rehberg, I. and Ahlers, G., Experimental Observation of a Codimension-Two Bifurcation in a Binary Fluid Mixture, preprint, 1985.

[22]Walden, R.W. and Ahlers, G., "Non-Boussinesq and Penetrative Convection in a Cylindrical Cell," J. Fluid Mech., Vol. 109, 1981, pp. 89-114.

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[23]Collins, D., Plessett, M.S., and Saffren, M.M., "Proceedings of an International Conference on Drops and Bubbles: Their Science and the Systems They Model," California Institute of Technology and Jet Propulsion Laboratory, Aug. 28-30, 1974 (2 vols.).

[24]Collins, D., Plessett, M.S., and Saffren, M.M., "Proceedings of the Second International Conference on Drops and Bubbles: Their Science and the Systems They Model," Jet Propulsion Laboratory, NASA 82-7, 1982.

[25]Tagg, R., Cammack, L., Croonquist, A., and Wang, T.G., "Rotating Liquid Drops: Plateau's Experiment Revisited," Jet Propulsion Laboratory 900-954, California Institute of Technology, Pasadena, CA, 1980.

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Electrodynamic Buoyancy Flows as Models of Planetary and Stellar Circulations

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Introduction

The space shuttle and space station laboratories provide a unique environment to do both fundamental and applied research on hydrodynamic systems, especially those involving forces that otherwise would be almost entirely obscured by gravitational effects in the terrestrial laboratory. There are many relatively weak surface stresses and body forces that may become dominant in low gravity. These include temperature- and concentration-dependent surface tension, temperature-dependent centrifugal forces, and forces arising from the action of electric fields on free or polarization charges embedded within a liquid. Fluid motions generated by this last group are the topic of this chapter.

Described here are research problems in so-called electrodynamic buoyancy flows that are driven by a coupling between thermal fluctuations in a fluid and by externally imposed electric fields. The class of motions generated by electric fields in an isothermal medium (primarily due to charge injection at the boundaries) are of less interest here because they generally are not masked by gravitationally induced buoyancy motions that occur only when there are density perturbations in a fluid. Incompressible flow in closed containers will be emphasized. Free-surface phenomena, which can be affected significantly by electrical stresses, are treated by Homsy and Donnelly in Chapter 8A. In a closed geometry there are two ways that temperature variations interact with electric fields to generate motions: through changes of either the dielectric constant or the electrical conductivity with temperature. Both cases are discussed here.

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Research in electrodynamic buoyancy flows, or "electroconvection," crosses many disciplines. There are fundamental questions of flow instability and transition to turbulence that remain unanswered and are of broad scientific interest. On the practical side, early work suggested that electrically induced motions could enhance the performance of certain types of heat exchangers. On a broader front, it has been shown that electrodynamic polarization effects can be used to generate radial buoyancy forces (i.e., radially directed and dynamically active body forces proportional to temperature) in a fluid contained between two rotating concentric spheres. This means that it is possible to conduct laboratory experiments that have the proper vector relationship between "gravity" and the rotation axis necessary to physically model large-scale flows in planetary and stellar atmospheres. Meteorologists, oceanographers, and astrophysicists have long recognized the importance of rotation and sphericity in determining the character of global circulations. Yet terrestrial laboratory experimentation concerned with modeling such circulations has been limited severely by the locally noncentral character of the uniform gravitational field of Earth. Thus, one of the major reasons for studying electroconvection in the low-gravity setting is the potential for addressing fundamental questions about the nature of motions in Earth's atmosphere and oceans, in other planetary atmospheres, and in stars.

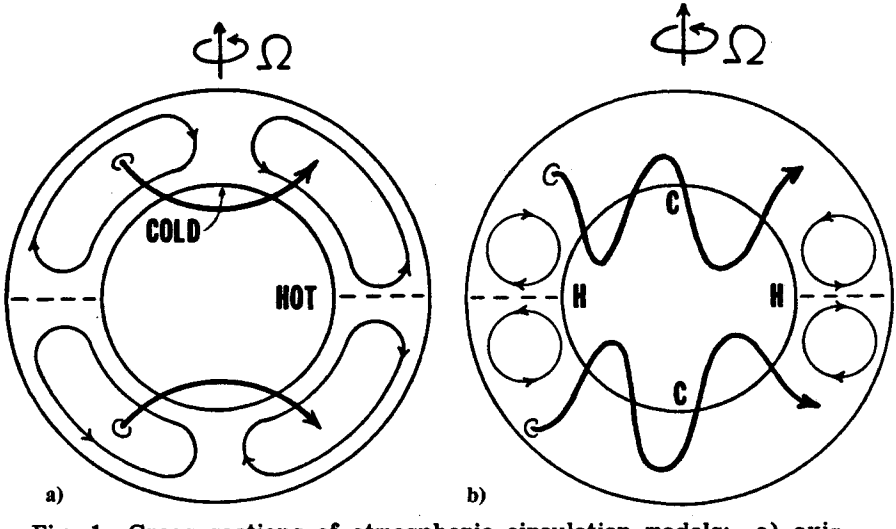

Fig. 1 Cross sections of atmospheric circulation models: a) axisymmetric Hadley models; b) nonaxisymmetric model.

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Many of the puzzles about planetary and stellar circulations arise from an inadequate understanding of a "simple" problem: given a rotating spherical shell of fluid with radial gravity subjected to a prescribed axisymmetric, but radially and/or latitudinally varying heating, what is the character of the thermally generated flow? To give an idea of the generality of this question and the many possible applications, a diverse set of astrophysical and geophysical examples are described. The limitations of terrestrial modeling are restated below, and some of the basic ideas behind spherical electroconvection are outlined. Relationships with other approaches, such as analytical and numerical modeling, are also addressed. Current work, including recent experiments onboard Spacelab 3 is outlined, and conclusions and suggestions for future low-gravity research are provided.

Planetary and Stellar Circulations

Earth's Atmosphere

The general circulation of Earth's atmosphere is one of the oldest and most studied subjects in fluid dynamics. Although there were earlier speculations, Hadley[1] presented one of the first truly scientific discussions of the problem. His model, shown in cross section in Fig. 1a, seems hopelessly oversimplified today, but many of its elements are still accepted. For example, he correctly concluded that the global circulation is driven primarily by the equator-to-pole temperature difference caused by an imbalance between incoming solar and outgoing infrared (IR) radiation at the surface. He proposed huge meridional cells with rising motion at the equator that, because of angular momentum conservation on a rotating planet, are accompanied by upper-level westerlies as shown in Fig. 1a.

It is now known that such a scheme does not agree with the observed water and angular momentum balance in the atmosphere, and that nonaxisymmetric waves dominate the transport of these quantities in midlatitudes. Smaller meridional circulations called "Hadley cells" do exist in the tropics when suitable longitudinal averages are taken. Bjerknes[2] and colleagues initiated this view (Fig. 1b), which has led to much study of the origins and properties of large-scale "planetary" waves. One area of recent research has focused on how planetary waves that arise from instability of the global Hadley cell break down and become chaotic (as Earth's weather most certainly is). Numerical and theoretical studies of very simple model sys-

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tems[3-5] have indicated that the route to chaos is in part similar to that proposed recently[6] as a universal transition scenario in a wide class of nonlinear dynamical systems. These and other similar low-dimensional models are a long way from faithfully representing the atmosphere. However, they represent one fruitful approach to understanding planetary-scale turbulence in at least some limiting range of parameters. Controlled experiments are needed to carefully explore and extend their predictions. A typical experiment that incorporates the key physical constraints of rotation, sphericity, and thermal driving by latitudinal heating at the bottom would follow the geometry of Fig. 1a. By varying the heating and rotation rate, the transition from the Hadley regime to the Bjerknes-Rossby regime and ultimately to turbulence could be studied. Would the turbulence contain coherent vortices as postulated by some theorists (see Leith[7])? If global topography were introduced, would multiple statistical equilibria and persistent features appear as predicted by simple models of mechanically forced flow on a sphere with no temperature variations?[8]

Solar Circulation

Although the surface of the sun shows a predominance of features with length scales much smaller than its radius, there has been speculation that there are very large-scale convective circulations called giant cells beneath the surface granulation.[9,10] These circulations are weak and difficult to detect, but recent attempts to use easily observed 5-min surface oscillations, which act as seismic probes of the internal structure of the sun,[11,12] may suggest their presence (Toomre, private communication, 1985). The giant cells are thought to span the convection zone that occupies the outer 20% or so of the solar envelope. They are a crucial ingredient in theories of the solar dynamo by which magnetic fields are maintained against ohmic dissipation and in explanations of solar differential rotation. Differential rotation is common to many bodies in the solar system (Jupiter and Saturn being other examples) and is simply the tendency for the surface or cloud layer to rotate faster at the equator than at the poles. In the sun, the equator rotates with a period of 25 days, whereas the pole rotates slower, with a period of about 35 days.[13]

Explanations of this differential rotation recently have been sought in terms of the transport of eastward momentum towards the equator by giant convection cells that are influenced by sphericity and rotation.[9,14] Laboratory

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experiments could help set the control parameter limits for this phenomenon. Because significantly higher model heating rates can be attained in the laboratory than can be practically studied using numerical models, analog experiments are useful in checking to see how low-resolution analytical and numerical theories hold up when external conditions are moved toward the more extreme values found for solar convection. For the sun, the simple geometry of Fig. 2a is appropriate. It rotates, but not sufficiently fast to be significantly oblate. Thus the time-averaged isotherms are nearly spherical, as are the geopotentials. There is anticipated to be little or no latitudinal variation of mean temperature; indeed, both the average surface temperature and heat flux from the sun appear to be independent of latitude.

Rapidly Rotating Stars

If a star is rotating rapidly enough to be significantly oblate, a global circulation will be generated that will look roughly like a reversed Hadley cell. This problem was worked on by Eddington[15] and others who realized

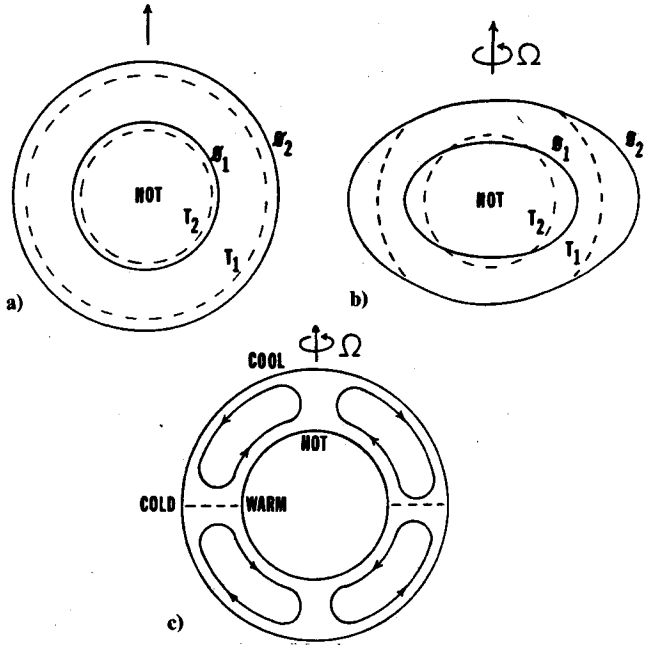

Fig. 2 Cross sections stellar circulation models: a) geopotentials (ϕ) and temperatures (T) for a nonrotating star; b) a rapidly rotating star; c) a spherical model of a rapidly rotating star.

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that because of thermal or radiative diffusion, the temperature contours in a rotating star would tend to be spherical. However, because the geopotentials or level surfaces are oblate, as one moves along a level surface from equator to pole, one encounters increasing temperatures. This relationship is shown in Fig. 2b. If a star is slightly oblate, the essence of the meridional circulations so generated can be captured in a spherical model that retains the crucial ingredient of a latitudinal temperature gradient, hotter at the pole, applied to the bounding surfaces (Fig. 2c). The meridional cells can be compared with those proposed by Hadley, as shown in Fig. 1a. In analytical studies of these so-called Eddington-Sweet circulations, such quasispherical models are commonly used.[16]

Once one has an axisymmetric circulation set up in a configuration like that shown in Fig. 2c, the following questions arise: what nonaxisymmetric convection modes are possible; will one get differential rotation; will these giant cells have the same orientations (primarily north-south) as those suggested for the sun in calculations by Busse[17] and Gilman?[9] When will large-scale turbulence set in? Answering these fundamental questions is very difficult because the basic instability problem is nonseparable and involves a two-dimensional background state. This simply means that enormous computational resources would be required to investigate such problems over a substantial range of the at least five-dimensional parameter space controlling even this simple model problem. Experiments on convecting spherical shells of fluid with radial gravity and prescribed boundary heating can suggest critical transition regions that may be profitably investigated numerically.

Giant Planets

Recent satellite missions have provided a wealth of information about the atmospheres of Jupiter and Saturn, and Voyager will soon pass Uranus. Much is yet to be understood about the banded structure of Jupiter and Saturn. From Voyager observations, Ingersol et al.[18] and Limaye et al.[19] suggest that the banded structure of Jupiter is maintained in part by small-scale momentum transfers at the edges of the bands. Busse[20] has proposed a theory based on the existence of giant convection cells oriented parallel to the axis of rotation deep in the interior of the planet below the cloud decks. Simple models[21,22] indicate that if there are substantial latitudinal temperature gradients in the Jovian atmosphere, the giant cells themselves would prefer an east-west orientation,

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thus leading naturally to the banded structure seen in the images.

These latter theories, which propose a radially uniform latitudinal temperature gradient ostensibly driven by solar heating, appear at odds with radiometer data. Ingersol[23] discusses the overall heat balance for Jupiter, and a sketch of his results is given in Fig. 3. The motions on both Jupiter and Saturn[24] are driven by solar heating and by an internal heat flux. This internal flux is being given up from the deep interiors as a result of slow gravitational collapse of these planets. For Jupiter, the emission temperature is almost constant at the level of the clouds, indicating that at this level there is at best only a small latitudinal temperature gradient. Concurrently, the IR emission to space is also independent of latitude. However, the solar flux absorbed by the atmosphere is about 0.9 relative units near the equator and approximately zero at the pole. To maintain an equilibrium, there must then be a convective flux up from the interior of the planet of roughly 0.5 units at the equator and 1.4 units at the pole. How does this come about? Rotation could affect interior convection differently at the equator and pole, or the degree of radial instability (the radial temperature drop) could be less at the equator, leading to weaker convection there. This would effectively mean that at the bottom of the convection zone, temperatures would be cooler at the equator than at the pole. Thus the physical model

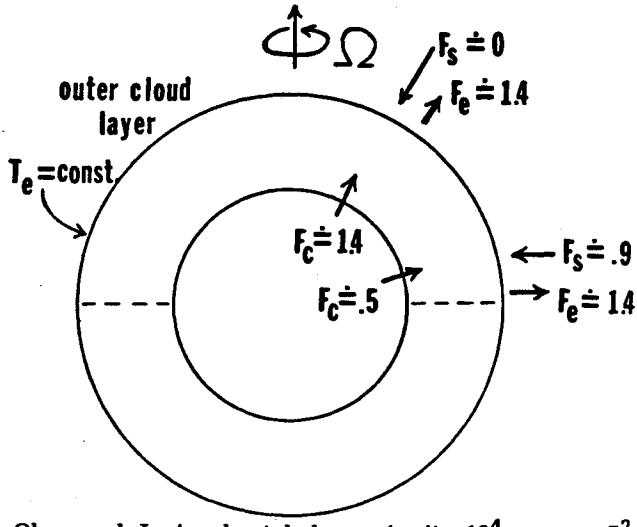

Fig. 3 Observed Jovian heat balance (units 10^4 ergs cm^{-2} sec^{-1}): F_s = Solar Flux; F_e = Emitted (IR) Flux; and F_c = Flux Through Convection Zone.

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corresponding to this case is similar to that proposed for oblate stars in Fig. 2c, but with a uniformly cool outer temperature.

Discussion of the dynamics of the atmosphere of Uranus are speculative, but there are suggestions that solar heating alone drives the atmospheric motions, and that the poles are warmer than the equator.[25,26] It is not known where, in the vertical dimension, the radiation is deposited.

Summary

It has been suggested that fundamental questions about the large-scale circulations of a number of planets and stars could be studied experimentally in the context of a simple model in which fluid is contained between two rotating differentially heated spheres with radial gravity. What distinguishes the different objects is the manner in which the heating is applied. This of course leads to vastly different circulations, made more complex by the effects of rotation, which can be either strong or weak depending on the rotation rate. Table 1 gives a summary of some model configurations.

Terrestrial and Low-Gravity Experiments

Parallel Plate Convection

The oldest type of terrestrial convection experiment is illustrated in Fig. 4a. Fluid is contained between two parallel plates that are differentially heated. The system can be set into rotation about the vertical axis. It is clear from the geometry of this situation that such experiments can be used to study thermal motions analogous to those on astronomical objects only in the immediate vicinity of the poles where gravity and rotation are aligned. It is

Table 1 Boundary heating distributions for models of planetary and stellar circulations

Object	Inner sphere	Outer sphere
Earth	Cool, hot equator	Warm
Sun	Hot, uniform	Cool, uniform
Rotating star	Warm, hot pole	Cold, cool pole
Jupiter	Warm, hot pole	Cold, uniform
Uranus	Cool, uniform	Warm, hot pole
Oceans	Cool, uniform	Warm, cold pole

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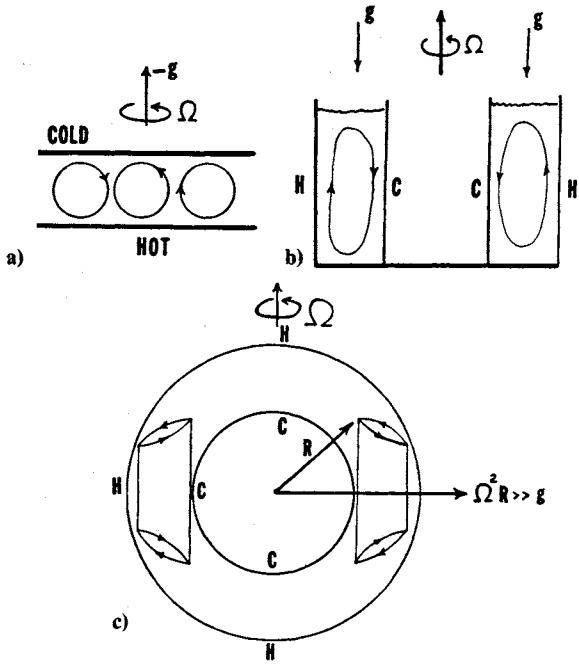

Fig. 4 Terrestrial laboratory models of thermal convection: a) rotating Bénard convection; b) annulus convection; c) centrifugal convection in spherical shell.

thus impossible to study the types of meridional circulations or planetary waves mentioned above.

Annulus Convection

A slightly different type of experiment was initiated in the early 1950s.[27,28] This is shown in cross section in Fig. 4b. A rotating cylindrical annulus contains a liquid and the outer rim is heated. Gravity again is aligned with the rotation axis. The heating of the outer rim and cooling of the inner wall may be thought of as a crude representation of the equator-to-pole temperature difference beneath Earth's atmosphere (Fig. 1a). Indeed, a sort of meridional Hadley circulation is set up for low heating rates, and this becomes unstable when nonaxisymmetric waves appear in the fluid as the heating differential is increased. This experiment exhibits a rich set of phenomena.[29,30] The waves appear much like atmospheric planetary waves, and studies of their interactions in this and similar experiments[3,31,32] have increased our understanding of complex dynamical processes occurring in the

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atmosphere. However, it is again clear that no element of sphericity is present in this experiment. Because curvature is crucial to planetary wave propagation, it would be most useful to see how the annulus results carry over to spherical systems that maintain the global relation between gravity and rotation.

Centrifugal Convection

Busse and Carrigan[33] devised an interesting experiment to look at giant cells in the equatorial regions of planetary and stellar atmospheres. If one rotates a spherical shell rapidly enough, the centrifugal force, which is proportional to density, will overwhelm gravity. As shown in Fig. 4c, this force is perpendicular to the rotation axis and hence allows the study of convection between differentially heated spheres near the equator. However, such an experiment does not allow for modeling of the coupling between the tropics and the midlatitudes or of the exploration of regions of parameter space where the planetary rotation rate is not extremely large. Essentially, such studies can look only at convection that is almost exactly aligned with the rotation axis.

Electroconvection in Spherical Shells

The geometry for a radial-gravity electroconvection experiment is shown in Fig. 5. A dielectric liquid is contained between two spheres. Arbitrary temperature distributions, which are functions of latitude, can be imposed

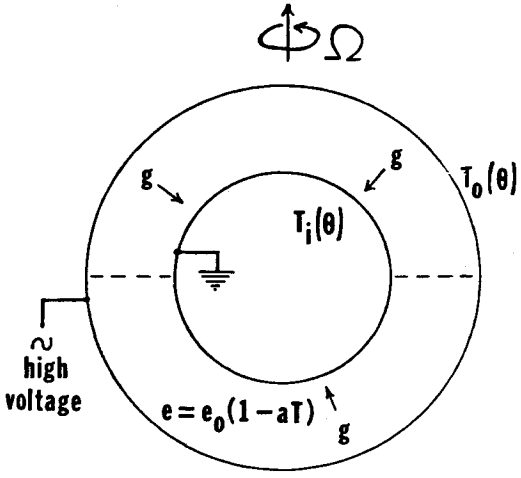

Fig. 5 Geometry for electrodynamic convection with radial gravity.

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on each spherical surface (see Table 1 for a guide to the possibilities). The essential ingredient that allows the generation of a radial buoyancy force in which hot fluid rises is that the dielectric constant e depends on temperature through the relation

$$e = e_0 (1 - a T) \quad (1)$$

Here e_0 is the ambient dielectric constant, a is the coefficient of thermal expansion, and T is the temperature. This equation just reflects that the macroscopic polarization is proportional to the fluid density (the number of polarizable molecules per unit volume), and the density in turn decreases with temperature. If the fluid has a long charge relaxation time, and the field oscillates rapidly, there will be no time-averaged free-charge forces. It can be shown[34] that the only dynamically active (vorticity-generating) electric force is then

$$F = -0.5\, e_0\, a\, T\, \nabla [E \cdot E(r)] \quad (2)$$

which is directed in the radial direction for an electric field E that depends only on spherical radius r. Note that this force is proportional to temperature and therefore is directly analogous to the usual vertically ($\hat{z}$) directed thermal buoyancy term

$$F = g\, a\, T\, \hat{z} \quad (3)$$

that appears on Earth. Now the electric field between two concentric spherical conductors each at constant potential will indeed be radial, so Eq. (2) provides exactly the correct radial gravity needed to study planetary and stellar circulations. Unfortunately, for available dielectric fluids the field strengths are limited by breakdown considerations to about 20 kV. For an experiment with a size large enough to get well beyond flows accessible numerically, the maximum effective radial gravity is of order 0.2 g. This is clearly a situation where terrestrial gravity masks the desired effect. Thus, a low-gravity environment is necessary to carry out modeling studies as outlined above. Another point is that the time scales for convection experiments usually are measured in terms of the fluid overturning time. Turbulence experiments require observations over many of these eddy time scales, which typically are tens of seconds. This, combined with a desire to cover many points in parameter space, leads to a requirement for many hours of continuous low gravity.

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Relationship to Computational Hydrodynamics

Typical Parameter Ranges

It was shown above that electrodynamic buoyancy flows in ac fields can be used to model a large class of astrophysical and geophysical flows. A question worth addressing is whether similar results could be obtained by fully three-dimensional computer solutions of the underlying hydrodynamical equations. The answer to this question largely depends on the parameter range accessible by any experiment and, of course, on how many experiments need to be done. Take the simple solar convection model (Fig. 2a) as an example. For fixed geometry and fluid type there remain two nondimensional control parameters that may be varied and that determine, apart from initial conditions, the character of the flows. The Rayleigh number, R_a, is a nondimensional measure of the magnitude of the buoyancy compared to dissipative mechanisms. It thus is one measure of the strength of the convection. The Taylor number, T_a, represents the relative strength of the rotation on the flow by comparing the rotation rate to the viscous diffusion rate. The details are irrelevant except to note that in this two-dimensional parameter space there will be regions where there are weak or no convective motions and regions where the convection will be very strong and highly turbulent. Figure 6 shows a regime diagram for thermal convection of this type. Below the so-called critical curves there is no convection. Moving vertically at fixed T_a, the convection becomes stronger and then turbulent. An experimental parameter range for a typical electroconvection experiment is shown as well. The upper limit on R_a of about 10^7 is a result of conservative estimates of the maximum voltage and heating rates for typical fluids. Experiments going well above 10^8 may be feasible. Note, however, that even at $R_a = 10^7$ one is already at a value about 10,000 times the critical points required for convection to first appear at moderate T_a.

Numerical Hydrodynamics

One can make a crude estimate of the amount of computation required to generate one solution of the three-dimensional hydrodynamic equations for a time equal to that required for a thermal pulse to diffuse across a typical laboratory annulus. This so-called thermal diffusion time is typically 1000 s. Numerical solutions are attained by representing the flow on a three-dimensional grid of points with spacing d, and then stepping the partial dif-

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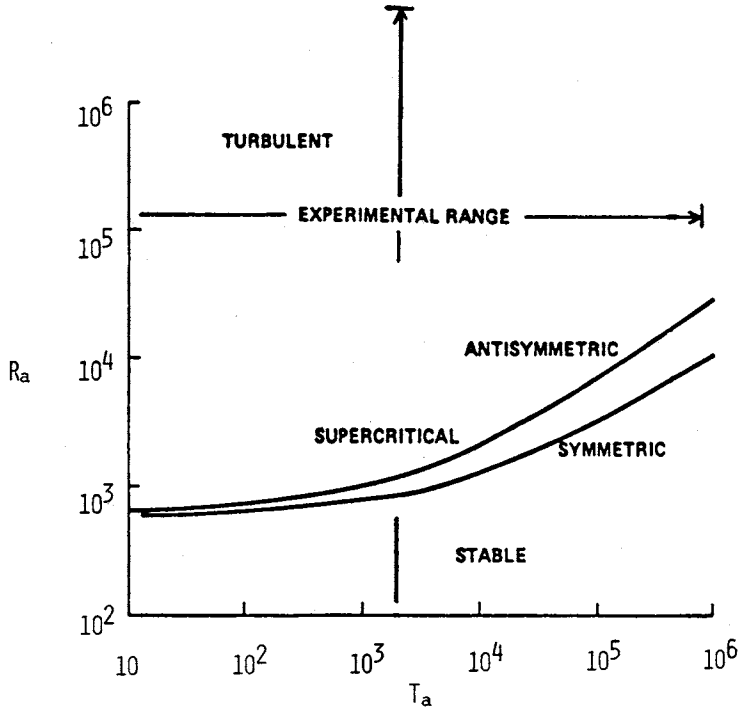

Fig. 6 Parameter ranges for a typical spherical convection experiment in low gravity.

ferential equations governing the fluid motion forward in time. Unfortunately, as the grid spacing is made smaller, the time step must be increased so that the solution remains computationally stable.

There should be several grid points across the smallest scale of convection, so that the motion is adequately resolved. As the Rayleigh number increases, thin "boundary" layers or thermal fronts appear. If their positions are known, the grid can be stretched to put points where they are needed. But in a turbulent flow, the boundary layers often separate erratically from the spherical walls, and it is necessary to fill the entire space with high-resolution elements. Models of convection[35] and observations in terrestrial laboratories[36] provide some evidence for the scale of these boundary layers. The fat ones scale roughly with $R_a^{-.25}$ times the depth of the layer. Being optimistic, one may assume that the thinnest layers with exponent 0.33 remain attached to the walls. If one settles for just four points across these "wide" layers, then covering a whole sphere requires about $(4\ \pi^2\ R_s^2/\text{depth}^2) \times 4^3 \times R_a^{.75}$ grid points, where R_s is the

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mean radius of the spherical annulus, typically three or four times the depth. The velocities are determined by balancing buoyancy and diffusion across the thin layers, and scale with $R_a^{.5}$. The numerical stability condition (where the maximum time step is given by the grid spacing divided by the velocity) then yields an estimate for the number of time steps. This is of order $R_a^{.75}$. At each grid point one is further required to evaluate complicated energy-conserving formulas for the advection of momentum and heat as well as invert a three-dimensional Poisson equation to solve for the pressure. In any case, a fairly conservative estimate is that at least 100 floating point operations (FLOPS) per grid point per time step will be required. Taking all this into account yields an estimate that more than $10^6 \times R_a^{1.5}$ FLOPS would be required to do the integration of the governing equations numerically. If one has to resolve the thinnest layers throughout the domain, then the exponent in this last expression is 2.0.

It is clear that as the Rayleigh number, R_a, increases the cost of computation rapidly becomes excessive. For example, at $R_a = 10^6$ about 10^{15} FLOPS need to be done. On a 1000-MegaFLOP-per-second supercomputer such as the Cray 2, this would take about 300 h. At $R_a = 10^7$, the number jumps to 10,000 h. In practice actual hydrodynamic codes run at least an order of magnitude slower than the maximum computing speed would suggest, so these time estimates are a bit optimistic. A recent model by Kerr[37] used 70 h of Cray 1 time to compute a flow for about one-hundredth of a diffusion time on a 128^3 mesh, using simpler (periodic) boundary conditions than are usually present in convection problems. These estimates and state-of-the-art results indicate that the cost to do even a few simulations at high Rayleigh number is astronomical.

Of course one probably would not proceed in such a brute-force way. One might run a lower resolution model (spectral or grid-point) at these high Rayleigh numbers, with the hope that the qualitative aspects of the solution would be correct. More complicated variable-mesh schemes (where dense grids move to where they are needed) may become practical, although they are difficult to vectorize to take full advantage of parallel processing. The role of experiments is clear. They can verify the qualitative and quantitative accuracy of truncated numerical models. They allow finer examination of an extended parameter space to identify key areas where careful numerical analysis with its elegant diagnostics can be used to further interpret and understand the observations. Because they can be

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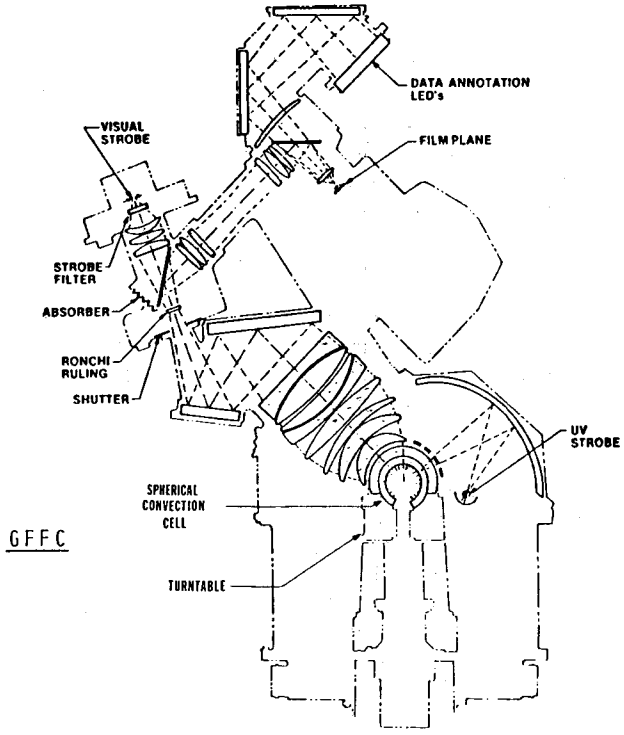

Fig. 7 Cross section of the geophysical fluid flow experiment.

run for long periods of time with slowly varying control parameters, they can investigate important properties like hysteresis in transitions between various states. Many recent observations of transition to chaos in various fluid systems, especially those using liquid metals, are well beyond current computational capabilities, and these are observations made at less than a hundred times critical. It appears that the most productive approach to many convection problems should in the future involve a combination of laboratory, computational, and theoretical modeling.

Current Work in Low-Gravity Electroconvection

An instrument that uses the polarization forces in an imposed radial field to simulate planetary and stellar convection has been built under the technical supervision of the NASA Marshall Space Flight Center and under the general and scientific supervision of the present author and J. Toomre of the University of Colorado. Figure 7 shows a cross section of the instrument. It consists of a

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central spherical convection cell that rotates under an optics housing. Thermal control loops built onto the turntable control the temperature on the inner and outer boundaries of the spherical capacitor, which contains the working fluid. The walls are electroplated with a transparent coating on the outside and a mirrored finish on the inside so that a large voltage may be maintained across the fluid in the cell. The flows are visualized by taking a time series of photographs of two distinct types. Dye lines are injected into the fluid photochromically by an ultraviolet flash and then are photographed as the fluid motions deform them. Also, folded optics are used as a back-focus Schlieren system. Thus, radially averaged horizontal temperature gradients of the whole hemisphere are reproduced in a series of photographs. The data are recorded on 16-mm film.

This experiment flew on Spacelab 3 (April 30-May 6, 1985), and a data set on a diverse collection of convective patterns was obtained. Some comments on the design history and typical shuttle operations may be of interest to those assessing the potential for low-gravity research in space. Most experiments proposing to look at phenomena masked by gravity are very sophisticated because complicated measurement technology is often necessary to look at weak effects with sufficient resolution and accuracy in a nonintrusive way. This, coupled with operational and safety requirements imposed on space hardware, means that research programs in low gravity are long-term efforts, often involving more than 5 years of development and testing. Will new technology, perhaps high-speed ultracomputers, come along to make the experiment obsolete before it flies? The techniques for running experiments in space are rapidly improving as more experience is gained. Data for the Spacelab test cited above were recorded on film because of the expense and uncertainty (justified as it turned out by the loss of two out of three Tracking and Data Relay Satellites [TDRS]) of getting vast amounts (gigabytes) of image data directly or indirectly to ground. Although unavoidable, this turned out to be unfortunate because the best way to operate a large class of fluid dynamics experiments is in the interactive mode, either via a payload specialist or via a downlink of at least some of the data. The essence of many of these experiments is to vary parameters, observing bifurcations and the like. If the experiment time scales are on the order of 1 h or less, real-time decisions can greatly improve the scientific return. Two methods of doing "hands-on" experiments are currently available: actual control via the astronaut or remote control via the experiment computer system. On

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Spacelab 3, the former route was slow because there was much competition for the single air-to-ground link. The latter was difficult to implement without committing a great amount of manpower and money and, with only one TDRS and a tendency for the onboard experiment computer to crash, perhaps was even less effective. These conditions should improve on future space shuttle flights, and the space station low-gravity module probably will be designed to make the interfaces for interactive experimentation easier to implement and operate. Then the true potential of many types of low-gravity experiments can be realized.

Areas for Future Research

Geophysical Fluid Dynamics

The experiment described above was designed to look at convection problems in systems that are radially unstable. This means that the basic boundary temperatures decrease outward. Some of the examples in Table 1, most notably Earth's atmosphere and the oceanic thermocline problem, involve predominantly stable situations where the basic temperature field increases radially outward almost everywhere. Problems of wave interactions, instability, and chaos in models of Earth's atmosphere already have been discussed. W. Fowlis of the Marshall Space Flight Center has investigated the possibility of constructing laboratory analogs to investigate these processes. The basic requirements imposed on such atmospheric general circulation models are rather stringent. The fluid layer must be considerably deeper, while still maintaining a large electrodynamic gravity field. This appears to be difficult to do, but research is continuing in this direction.

If a statically stable model of Earth's atmosphere can be constructed, it then would be interesting to consider inserting topography so that global flow around mountains might be studied. Further, the spherical annulus could be broken up into basins by placing meridional barriers between the bounding spheres. With sufficient remote-sensing instrumentation (temperature and velocity profilers), a significant contribution to our understanding of the oceanic thermocline circulation could be made. There has been much recent interest in this subject.[38,39] Here the curvature of the oceans due to the sphericity of Earth is crucial to the dynamics. There is a real need for insight into the qualitative nature of buoyancy circulations in closed gyres. What are the shapes of the circulations for various degrees of forcing? Where are the boundary

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layers and what are their functions? Where are the sinking regions? What is the extent of small-scale turbulent sinking in these regions, and how are these motions coupled to the mostly laminar large-scale thermocline circulation? These are just some of the problems that could benefit from experimental guidance.

Electroconvection with dc Fields

This chapter has concentrated on electroconvection in the presence of an ac field. Thermally driven electroconvection is also possible in dc fields. The mechanism for "buoyancy" is the accumulation of free charge in a weakly conducting fluid that is acted on by the Coulomb force. If the conductivity is a function of temperature, then thermal fluctuations will affect the charge distributions and various motions and instabilities become possible. There have been many studies of the basic Bénard configuration (Fig. 4a) with constant electric potentials on the boundaries. Turnbull[40] observed this class of flow in the terrestrial laboratory. His observations were followed by many theoretical and experimental works[41-45] that have attempted to sort out the different thermal and nonthermal (charge-injection) mechanisms that can occur. For the thermally generated motions, where the conductivity current is much greater than the injection current, the typical electrodynamic interactions overwhelm gravitational buoyancy only at very small plate separation. Unfortunately, it is precisely at these small distances (< 1 mm) that unwanted charge-injection effects can creep in. Thus, it would be useful to consider some simple electroconvection experiments in low gravity to isolate the electrodynamic buoyancy mode in this problem from other perturbations.

Of primary fundamental interest is that even in the absence of gravity, certain of the thermal instability modes arise as an overstability (or Hopf bifurcation) where an oscillating rather than a monotonic or nonoscillating disturbance grows. These play an important role in modern theories and observations of transition to turbulence,[46] and it would be beneficial to conduct experiments on a system whose primary, instead of secondary or tertiary, instability is of this type. There are, however, many technical questions involved with experimental controls, electrical boundary conditions, and flow visualization in this area of research.

References

[1]Hadley, G., "Concerning the Cause of the General Trade Winds," Phil. Trans., Vol. 29, 1735, pp. 58-62.

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AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[2]Bjerknes, V., "On the Dynamics of the Circular Vortex with Applications to the Atmosphere and Atmospheric Vortex and Wave Motions," Geophys. Publ., Vol. 2, No. 4, 1921, 88 pp.

[3]Pedlosky, J., "A Model of Wave Amplitude Vacillation," J. Atmos. Sci., Vol. 34, 1977, pp. 1898-1912.

[4]Pedlosky, J. and Frenzen, C., "Chaotic and Periodic Behavior of Finite Amplitude Baroclinic Waves," J. Atmos. Sci., Vol. 37, 1980, pp. 1177-1196.

[5]Pedlosky, J. and Young, W.R., "Ventilation, Potential-Vorticity Homogenization and the Structure of the Ocean Circulation," J. Phys. Ocean., Vol. 13, 1983, pp. 2020-2037.

[6]Feigenbaum, M.J., "Universal Behavior in Nonlinear Systems," Physica D, Vol. 7, 1983, pp. 16-39.

[7]Leith, C.E., "Dynamically Stable Non-linear Structures," Problems and Prospects in Long and Medium Range Weather Forecasting, edited by D. M. Burridge and E. Kallen, Springer Verlag, NY, 1984.

[8]Legras, B. and Ghil, M., "Persistent Anomalies, Blocking and Variations in Atmospheric Predictability," J. Atmos. Sci., Vol. 42, 1985, pp. 433-471.

[9]Gilman, P.A., "Non-linear Dynamics of Boussinesq Convection in a Deep Rotating Spherical Shell," Geophys. Astrophys. Fluid Dyn., Vol. 8, 1977, pp. 93-135.

[10]Howard, R. and Yoshimura, H., "Differential Rotation and Global Scale Velocity Fields," Proc. I.A.U. Sympos., No. 71, 1976.

[11]Duvall, J.L. and Harvey, J.W., "Rotational Frequency Splitting of Solar Oscillations," Nature, Vol. 310, 1984, pp. 19-21.

[12]Duvall, J.L., Dziembowski, W.A., Goode, P.R., Gough, D.O., Harvey, J.W., and Leibacher, J.W., "Internal Rotation of the Sun," Nature, Vol. 310, 1984, pp. 22-24.

[13]Howard, R. and Harvey, J.W., "Spectroscopic Determinations of Solar Rotation," Solar Phys., Vol. 12, 1970, pp. 23-51.

[14]Busse, F.H. and Hood, L.L., "Differential Rotation Driven by Convection in a Rapidly Rotating Annulus," Geophys. Astrophys. Fluid Dyn., Vol. 21, 1982, pp. 59-74.

[15]Eddington, A.S., The Internal Constitution of Stars, Cambridge University Press, Cambridge, England, 1926.

[16]Tassoul, J-L, Theory of Rotating Stars, Princeton University Press, Princeton, NJ, 1978.

[17]Busse, F.H., "Thermal Instabilities in Rapidly Rotating Systems," J. Fluid Mech., Vol. 44, 1971, pp. 441-460.

Downloaded by RMIT BUNDOORA LIBRARY on August 15, 2015 | http://arc.aiaa.org | DOI: 10.2514/4.865824

AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[18]Ingersol, A.P., Beebe, R.F., Mitchell, J.L., Garneau, G.W., Yagi, G.M., Müller, J-P, "Interaction of Eddies and Mean Zonal Flow on Jupiter as Inferred from Voyager 1 and Voyager 2 Images," J. Geophys. Res., Vol. 86, 1980, pp. 8733-8743.

[19]Limaye, S.S., Reverromb, H.E., Sromovsky, L.A., Krauss, R.J., Santek, D.A., Soumi, V.E., Collins, S.A., and Aris, C.C., "Jovian Winds from Voyager 2. Part 1: Zonal Mean Circulation," J. Atmos. Sci., Vol. 39, 1982, pp. 1413-1432.

[20]Busse, F.H., "A Model of Mean Zonal Flows in the Major Planets," Geophys. Astrophys. Fluid Dyn., Vol. 23, 1983, pp. 153-174.

[21]Flaser, F.M. and Gierasch, P.J., "Turbulent Convection Within Rapidly Rotating Superadiabatic Fluids With Horizontal Temperature Gradients," Geophys. Astrophys. Fluid Dyn., Vol. 10, 1978, pp. 175-212.

[22]Hathaway, D.H., Toomre, J., and Gilman, P.A., "Convective Instability When the Temperature and Rotation Vectors are Oblique to Gravity," Geophys. Astrophys. Fluid Dyn., Vol. 15, 1980, pp. 7-37.

[23]Ingersol, A.P., "Pioneer 10 and 11 Observations and the Dynamics of Jupiter's Atmosphere," Icarus, Vol. 29, 1976, pp. 245-253.

[24]Smith, B.A., Soderblom, L., Beebe, R., Boyce, J., Briggs, G., Brnker, A., Collins, S.A., Hansen, C.J., Johnson, T.V., Mitchell, J.L., Terrile, R.J., Carr, M., Cook A.F. II, Cuzzi, J., Pollack, J.B., Danielson, G.E., Ingersol, A., Davies, M.E., Hunt, G.E., Masursky, H., Shoemaker, E., Morrison, D., Owen, T., Sagan, C., Veverka, J., Strom, R., Soumi, V., "Encounter with Saturn: Voyager 1 Imaging Science Results," Science, Vol. 212, 1982, pp. 163-191.

[25]Stone, P.H., "The Atmosphere of Uranus," Icarus, Vol. 24, 1975, pp. 292-298.

[26]Hunt, G.E., Uranus and the Outer Planets, Cambridge University Press, Cambridge, England, 1982.

[27]Hide, R., "An Experimental Study of Thermal Convection in a Rotating Liquid," Phil. Trans. Roy. Soc. A, Vol. 250, 1958, pp. 441-478.

[28]Fultz, D., et al., "Studies of Thermal Convection in a Rotating Cylinder With Applications for Large-scale Atmospheric Motions," Meteor. Mongro., Vol. 4, 1959, 1044 pp.

[29]Hide, R. and Mason, P.J., "Sloping Convection in a Rotating Fluid," Adv. Phys., Vol. 24, 1975, pp. 57-100.

[30]Hignett, P., "Characteristics of Amplitude Vacillation in a Differentially Heated Rotating Fluid Annulus," Geophys. Astrophys. Fluid Dyn., Vol. 31, 1984, pp. 247-282.

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AIAA The World's Forum for Aerospace Leadership Purchased from American Institute of Aeronautics and Astronautics

[31]Hart, J.E., "A Laboratory Study of Baroclinic Instability," Geophys. Fluid Dyn., Vol. 3, 1972, pp. 181-209.

[32]Lindzen, R.S., Farrel, B., and Jacquin, D., "Vacillations Due to Wave Interference with Applications to the Atmosphere and to Annulus Experiments," J. Atmos. Sci., Vol. 39, 1982, pp. 14-23.

[33]Busse, F.H. and Carrigan, C.R., "Laboratory Simulation of Thermal Convection in Rotating Planets and Stars," Science, Vol. 191, 1976, pp. 81-83.

[34]Hart, J.E., "Studies of Earth Simulation Experiments," NASA CR-2753, 1976, 66 pp.

[35]Robinson, J.L., "Finite Amplitude Convection Cells," J. Fluid Mech., Vol. 30, 1967, pp. 577-600.

[36]Deardorff, J.W. and Willis, G.E., "Turbulent Convection Between Horizontal Plates," J. Fluid Mech., Vol. 28, 1967, pp. 675-704.

[37]Kerr, R.M., "Higher Order Derivative Correlations and the Alignment of Small-scale Structures in Isotropic Numerical Turbulence," J. Fluid Mech., Vol. 153, 1985, pp. 31-58.

[38]Luyten, J., Stommel, H., and Pedlosky, J., "The Ventilated Thermocline," J. Phys. Ocean., Vol. 13, 1983, pp. 292-309.

[39]Rhines, P. and Young, W.R., "A Theory of the Wind-driven Circulation," J. Marine Res., Vol. 40, 1982, pp. 559-596 and 849-865.

[40]Turnbull, R.J., "Electroconvective Instability With a Stabilizing Temperature Gradient," Phys. Fluids, Vol. 11, 1968, pp. 2597 and 2603.

[41]Roberts, P.H., "Electrohydrodynamic Convection," Q. J. Mech. and Appl. Maths., Vol. 22, 1969, pp. 211-220.

[42]Hopfinger, E.P. and Gross, J.P., "Charge Transport by Self-generated Turbulence in Insulating Liquids Submitted to Unipolar Injection," Phys. Fluids, Vol. 14, 1971, pp. 1671-1682.

[43]Bradley, R., "Overstable Electroconvective Instabilities," Q. J. Appl. Mech. Appl. Maths., Vol. 31, 1978, pp. 381-390.

[44]Atten, P. and LaCroix, J.C., "Nonlinear Hydrodynamic Stability of Liquids Subject to Unipolar Injection," J. de Mecanique, Vol. 18, 1979, pp. 469-510.

[45]Worraker, W.J. and Richardson, A.T., "A Non-linear Electrohydrodynamic Stability Analysis of a Thermally Stabilized Plane Layer of Dielectric Liquid," J. Fluid Mech., Vol. 109, 1981, pp. 217-237.

[46]Swinney, H., "Observations of Order and Chaos in Non-linear Systems," Physica D., Vol. 7, 1983, pp. 3-15.

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Comments on Fluid Dynamics

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Homsy and Donnelly's initial premise that the use of the low-gravity environment is "routine" is contradicted by current experience. Space experiments are expensive, complicated, and require long lead times. Some of these conditions should improve in the future, but with factors such as the heavy load schedules for NASA's shuttle and the rigid safety and operations restrictions, it is doubtful that in 5 years, if ever, it will be as routine to perform experiments in low gravity as it is in terrestrial laboratories. Thus, it seems necessary to identify carefully and to emphasize the fluid phenomena that would be different or unique in space.

Homsy and Donnelly present an interesting and different view in attempting to categorize the important low-gravity fluid physics research topics. However, the examples cited do not appear to have much relation to the important turbulence or chaos questions raised, although there are certainly many interesting instability phenomena worthy of study. There are also interesting phenomena involving coupled and nonlinear systems.

Regarding the remarks on how well theoretical and numerical studies can help resolve the problems cited (i.e., those with multiple length and time scales), note that such problems can be made computable by careful scale analyses that identify for retention the dominant and important physics. In this way, meaningful simplified models can be reasonably studied.

It is not clear what Homsy and Donnelly mean by the statement "gravity complicates the interpretation of experimental results." If experiments are performed terrestrially and gravity plays an important role, then how could it "complicate the interpretation"? Buoyancy clearly affects dendrite formation on Earth; in space, dendrite formation may be quite different and, therefore, require study. How-

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ever, how will low-gravity studies be related to those at one gravity? The problem arises with many low-gravity experiments proposed; that is, how will low-gravity results give deeper understanding of phenomena in which gravity truly contributes importantly? To observe the differences in a phenomenon under the two different gravity levels is important in itself.

The distinction between cases 2 and 4 presented by Homsy and Donnelly is not clear. For case 3, what is meant by a "good theory" is again obscure. The proper definition is that it is a theory in which the dominant mechanisms at least are included. Therefore, if one is to be "faithful to both the complicated chemistry and fluid flow" of combustion on Earth, a "good theory" must include buoyancy. For this purpose, advantage has not yet been taken of the multiple time scales inherent in combustion problems to obtain more tractable and appropriate theories. There is, however, merit in studying combustion in a low-gravity environment because of a real possibility of fires aboard spacecraft.

Case 4 (gravity limits the length scale of experiments) may be the most compelling. In the parameters presented in this case, the thermal diffusivity is omitted from the Marangoni number definition, and the capillary number as presented is a rather specific one, limited to situations (such as the Marangoni instability) in which the characteristic velocity is the thermal diffusion velocity (κ/d). For that case it has been called the Crispation number. More generally, the Crispation number is given as $Ca = \mu U_R/\sigma$, where U_R is the proper reference velocity. For viscous thermocapillary flows for which $U_R = \sigma_T \Delta T/\mu$, the capillary number is equal to $\sigma_T \Delta T/\sigma = G_D/G_o$, where G_D is another important parameter called the dynamic Bond number. The dynamic Bond number should be included in the list presented because it is essentially an indication of the relative importance of buoyancy to thermocapillary forces. It is essential that the proper dimensionless parameters be used, for they provide one of the most powerful means for obtaining meaningful (theoretical and experimental) models of real phenomena.

The example presented by Homsy and Donnelly to indicate the scale limitations in making thermocapillary flows dominant in a 1-g environment is valid in a gross sense. However, by heating a fluid layer with a free surface from above so that some thermal stratification occurs to reduce buoyancy (Kamotani et al.), local thermocapillary flows were observed in layers centimeters deep.[1] This is an example of how ingenuity can be used to obtain information under seemingly impossible conditions. Incidentally,

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surface temperature distributions were obtained in experiments on small, simulated floating zones.

The discussion on minimizing the effect of gravity on free surface shapes must be understood to apply to isothermal static-free surfaces. When a thermocapillary flow occurs, deflections of the free surface due to the flow are independent of gravity and are determined by the capillary and Weber numbers.

In summary, a plethora of worthwhile topics has been presented for study in a low-gravity environment. Most of the comments herein address interpretation and usefulness of the results based on the present author's desire to understand these phenomena as they occur in nature. Therefore, it is not clear how elimination from a process of a dominant mechanism such as gravity can improve the understanding of it. If the real process is complex, better theoretical and experimental approaches must be used; for example, microminiature sensors may need to be developed to make measurements on a smaller scale. By analogy, there was a period when high-Mach-number flows could be established only for very small times in shock tubes. This led to the development of instrumentation with sufficiently rapid response to yield meaningful data. Because many of the phenomena described are different in a low-gravity environment, and long-residence times under such conditions are becoming a reality, research may be justified on that basis alone.

Hart deals with several interesting and complex problems concerning planetary and stellar circulations and considers a novel experimental approach to the study of some of their aspects. The primary basis for the use of a low-gravity environment for Hart's research is to be able to impose radial buoyancy forces on a fluid contained between two rotating concentric spheres. Electroconvection provides the means to achieve this, but its effects would be overwhelmed by gravity on Earth.

The emphasis in Hart's experiment is placed on obtaining the proper vector relationship between "gravity" and the rotational axis for proper physical modeling. However, other parameters must also be considered. First, the Grashof number must be extremely large on the astrophysical and geophysical scales of interest. Figure 6 of Hart's paper shows an experimental Rayleigh number of about 10^5. His text refers to an upper limit of 10^7 for a simple solar convection model. The Grashof number, however, is the parameter that properly describes the flow. Since an incompressible fluid is used, the Grashof number must be at least an order of magnitude lower than the Rayleigh number. Also, the experimental Prandtl number

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is not in accord with that for gases. Thus, the flow and thermal boundary layers will not be properly simulated. Has any thought been given to other body forces for achieving similar modeling on Earth? For example, how about electromagnetic forces, which can be controlled by changes in current and magnetic field and permit the use of a gas?

Considerable emphasis is placed on the transition to chaos and other instabilities. This is somewhat surprising when it is stated that even the "simple" problem of the nature of the flow is not known. Would it not be better to obtain better understanding of the basic flows before attempting to study the much more complex flow transitions?

One might also wonder whether the difficulties of numerical studies are not overemphasized. Because the details of the experiment are not presented, it is not possible to determine whether more information is being asked from the computer than from the experiment. These questions are raised in the spirit previously stated, namely, that the space experiments should be as effective and meaningful as possible.

The present author's main points are restated as follows:

- Clear justification and detailed definition should be given for proposed space-flight experiments. This may require considerable ground-based research. More convincing arguments should be presented to justify space-flight experiments for clarifying terrestrial phenomena.
- Much more careful and precise use should be given to proper use of dimensionless parameters to ensure proper simulation of the phenomena of interest.
- Availability of high-speed computers seems to have precluded serious analysis of complex phenomena.
- Much better theories might be developed by combining analysis with computation. The use of multiple time and length scales, which have not been sufficiently used, offers opportunities to do this.

In the first survey of low-gravity fluid flows, a number of different types of fluid flows have been identified that can occur under low-gravity conditions.[2] Some, such as buoyancy-driven and g-jitter convection, are acceleration-field dependent. Others, such as surface-tension gradient, thermoacoustic, and phase-change convection are independent of the acceleration field. Although most of

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these could also occur under normal gravitational conditions, they are usually overshadowed by other flows except under rather limited conditions. Thus, they have received relatively little attention. However, in a low-gravity environment they can become significant and, therefore, more careful study of them is required. It is also possible that two or more forces can act simultaneously. Their combined action can result in unusual flows. The little work that has been done on such problems pertains to very specific situations, so that flows due to coupled forces are not, as yet, predictable.

Of the various topics described above, most emphasis has been given to thermocapillary flows, not only because of their inherent scientific interest, but also because of their importance to the containerless processing of materials. Some work also has been done on g-jitter convection. Combined theoretical and experimental work on the flow generated by g-jitter in a completely confined fluid is reported by Kamotani et al.[3] The more complex problem of g-jitter effects on free surfaces received some attention in the 1960s, in relation to liquid rocket fuel sloshing. Recently, drop-tower tests and analyses have been performed to gain a better understanding of this phenomena. Much more research on this problem is required.

Aside from the little work summarized in this review, this author knows of no ongoing considerations of thermoacoustic or phase-change convection. Both of these warrant further study. Finally, phase-separation phenomena will certainly be different in space and this opens new areas for research. It is clear that there are many important and exciting low-gravity problems in the fluid and thermal sciences that warrant research efforts.

References

[1]Kamotani, Y., Ostrach, S., and Lowry, S., "Materials Processing in the Reduced Gravity Environment of Space," Materials Resource Soc. Symposia Proc., Vol. 9, 1982, pp. 161-172.

[2]Ostrach, S., "Low-Gravity Fluid Flows," Annual Review of Fluid Mechanics, Vol. 14, 1982, pp. 313-345.

[3]Kamotani, Y., Prasad, A., and Ostrach, S., "Thermal Convection in an Enclosure Due to Vibrations Aboard Spacecraft," AIAA Journal, Vol. 19, 1981, pp. 511-516.

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Appendix A. Acronyms and Abbreviations

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Acronyms and Abbreviations

A	ampere
ac	alternating current
AFWP	Wright-Patterson Air Force Base
Al	aluminum
alt	altitude
ASTP	Apollo-Soyuz Test Project
bps	bits per second
C	carbon
^{o}C	degrees Celsius
Ca	Crispation number
C_a	Capillary number
Cd	cadmium
cgs	centimeter-gram-second units
Cl	chlorine
cm	centimeter
Cy	cyclohexane
DARPA	Defense Advanced Research Projects Agency
dc	direct current
diam	diameter
DOD	Department of Defense
D	deuterium
F	fluorine; farad (as used in Chapter 3A)
FETs	field-effect transistors
FLOPS	floating point operations
ft	feet
G	gravitational constant; Bond number (as used in Chapters 8A and 8C)
G_D	dynamic Bond number
Ge	germanium
gm	gram
G_R	Grashof number
h	hour
H	hydrogen
He	helium
^{3}He	isotope of helium with atomic weight of 3
^{4}He	isotope of helium with atomic weight of 4
He-I	liquid helium above the lambda point
He-II	liquid helium below the lambda point
Hg	mercury
Hz	hertz

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ICF	inertial confinement fusion
in.	inch
In	indium
IR	infrared
k	kilo
K	degrees kelvin
kG	kiloGauss
LAGEOS	Italian satellite system
lbs	pounds
m	meter
M	mega
M_a	Marangoni number
MCZ	Magnetic Czochralski Pulling
Me	methanol
min	minute
mm	millimeter
Mn	manganese
μm	micrometer
n	nano
NASA	National Aeronautics and Space Administration
Nd	neodymium
NG	nucleation and growth
n.mi.	nautical mile
NSF	National Science Foundation
p	pico
PACE	Physics and Chemistry Experiments
PI	principal investigator
psf	pounds per square foot
psia	pounds per square inch absolute
psig	pounds per square inch guage
R_a	Rayleigh number
RG	Renormalization Group
s	second
Se	selenium
Si	silicon
SPAR	Space Processing Applications Rocket
SQUID	Superconducting Quantum Interferometer Device
STAMPS	Scientific and Technological Aspects of Materials Processing in Space (Report and Committee)
STS	Space Transportation System
T	tritium
Ta	Taylor number
TDRS	Tracking and Data Relay Satellite
Te	telluride
U.S.	United States
USSR	Union of Soviet Socialist Republics

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V	volt
W	watt
Xe	xenon
Z	atomic number
Zn	zinc

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Appendix B. Microgravity Science and Applications: Experiment Apparatus

The following pages are reprinted from *Microgravity Science and Applications: Experiment Apparatus and Facilities*, NASA Microgravity Science and Applications Division, Washington, D.C., 1985

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GENERAL PURPOSE ROCKET FURNACE

EXPERIMENTAL CAPABILITY The General Purpose Rocket Furnace (GPRF) provides three independently controlled cavities for melting and resolidifying experimental specimens in a microgravity environment. Each cavity can be operated to provide near-isothermal or gradient temperature profiles. Samples can be cooled at specified rates with a cold gas quench through a common manifold or water-cooled heat sink integral with each cavity while maintained in a sealed atmosphere.

MODE OF OPERATION Each cavity consists of a three zone furnace with heat extraction at one end, capable of operating in an isothermal or gradient mode. The temperature gradient is maintained by programmable control of the three heating elements and a heat exchanger in the cavity. The isothermal environment is provided by operating the three heating elements at or as near the same temperature as is possible.

OPERATIONAL PARAMETERS

Operating Temperature Range	100° C-900° C
Maximum power	1600 watts

SAMPLE PARAMETERS

Maximum Length	7.8 cm
Maximum Diameter	2.0 cm

PHYSICAL CHARACTERISTICS

Furnace length	50.80 cm
Furnace diameter	43.18 cm
Furnace weight	63.56 kg

INTEGRAL INSTRUMENTATION Maximum of two thermocouple measurements per sample.

DATA ACQUISITION CAPABILITIES Real time data acquisition is not applicable to this unit. Analysis is performed on the finished samples and on the digital temperature data provided by the thermocouples.

FACILITY INTEGRATION OPTIONS Presently the GPRF is designed to operate in the Materials Experiment Assembly (MEA) in the Orbiter payload bay.

ADDITIONAL NOTES

NASA plans to modify the two GPRF's to increase their operating time and temperature capabilities after the MEA-A3 (D-1) Mission which is scheduled in the latter part of 1985.

Further information may be obtained from Kenneth R. Taylor/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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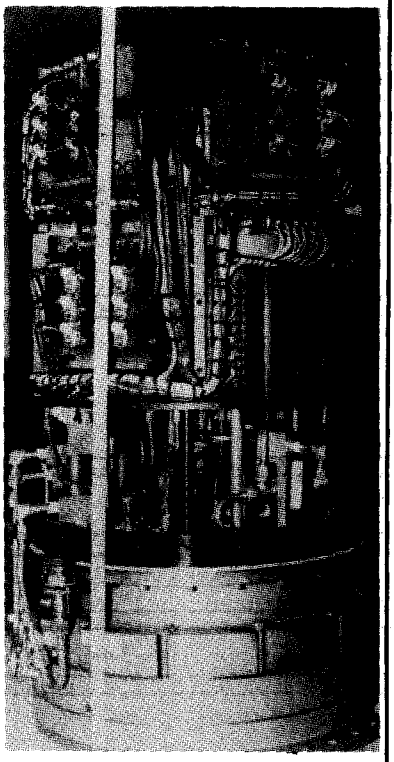
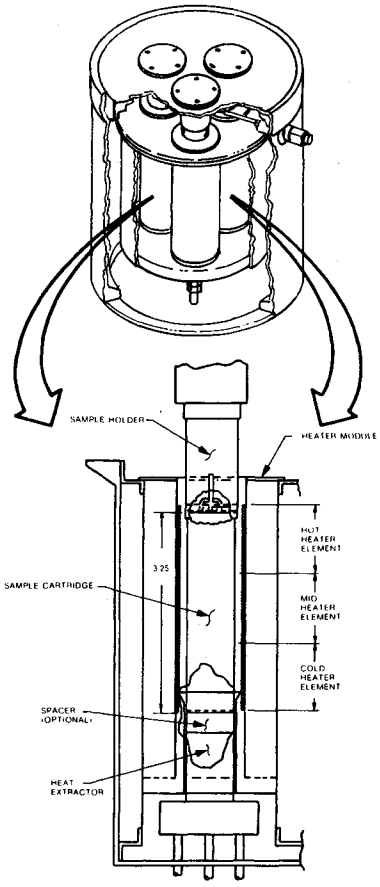
GENERAL PURPOSE ROCKET FURNACE

PHOTOGRAPHIC VIEW



SCHEMATIC VIEW



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AUTOMATED DIRECTIONAL SOLIDIFICATION FURNACE

EXPERIMENTAL CAPABILITY The Automated Directional Solidification Furnace (ADSF) is used to individually melt up to four different material samples. Each sample can then be cooled at a controlled rate with 50-50 ethylene glycol/water in a manner which will promote directional solidification. Up to two rate changes can be achieved during the processing of each sample. The process allows investigation into the anisotropic properties of metals and the unusual electrical, magnetic, and optical properties of unique directionally solidified molecular structures.

MODE OF OPERATION Four separate furnace heating units are present, consisting of an individual heater module and copper quench block. Each heating unit is translated along the axis of the sample during the melt process. Cooling is accomplished as the water cooled copper quench block is translated along the sample axis. The drive system is variable speed with microprocessor control of the translation speed and any required rate change. Atmospheric and environmental control are maintained by the sealed furnace enclosure.

OPERATIONAL PARAMETERS

Translation speed	0.1 mm/hr. to 500 mm/hr.
Operating temperature	200-500°C (middeck) 200-1500°C (cargo bay)
Voltage	28 vdc ± 4 volts
Power	1,175 watts*

SAMPLE PARAMETERS

Capacity	4 samples
Ampoule length (high temperature version)	135 mm
diameter	6 mm
length (low temperature version)	135 mm
diameter	6-8 mm

PHYSICAL CHARACTERISTICS The ADSF will include two Experiment Apparatus Containers (EAC's) having a total control weight of 77.1 kg.

INTEGRAL INSTRUMENTATION Two furnace cavities will each contain four thermocouples while the remaining two furnace cavities will each contain one thermocouple.

DATA ACQUISITION CAPABILITIES Up to 22 channels of data may be recorded at a rate of 1 sps.

FACILITY INTEGRATION OPTIONS The unit will be housed in two EAC's mounted in either the Orbiter Middeck or Payload Bay.

ADDITIONAL NOTES

*Maximum power capability; the ADSF will have a peak power of 357 watts when configured in EAC's mounted on the Material Science Lab (MSL-2) in the Orbiter Payload Bay. The ADSF is planned for flight in 1985.

Further information may be obtained from James A. Fountain/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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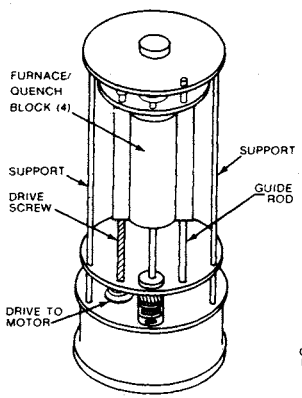
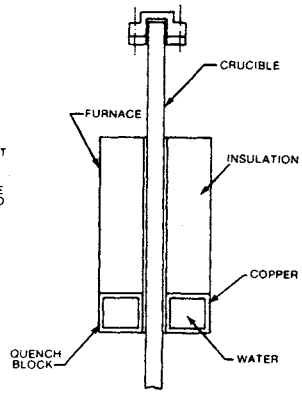
AUTOMATED DIRECTIONAL SOLIDIFICATION FURNACE

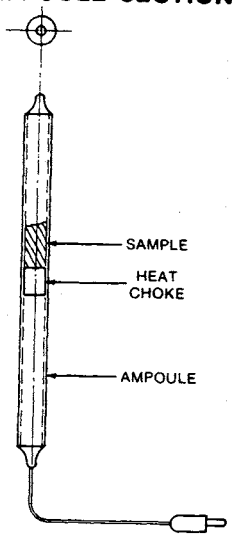
APPARATUS (simplified)



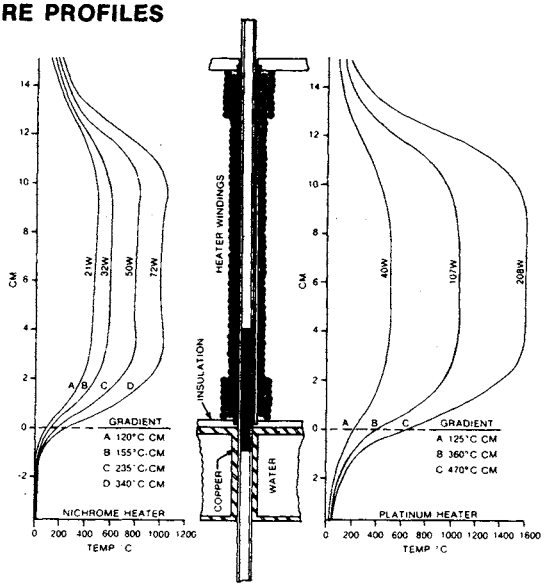
FURNACE SECTION



AMPOULE SECTION



TEMPERATURE PROFILES



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ADVANCED AUTOMATED DIRECTIONAL SOLIDIFICATION FURNACE

EXPERIMENTAL CAPABILITY This advanced design of a directional solidification furnace (AADSF) has a sophisticated controlled gradient region between the hot and cold zones. The furnace may be configured to an individual experimenter's sample and operated to compensate for changes in solidus temperature as the sample adjusts to its steady state value, changes in thermal conductivity between solid and melt, and energy deposition from sample translation and release of latent heat. The unit is capable of maintaining the solidification front in optimum position for obtaining a nearly planar interface.

MODE OF OPERATION The microprocessor controlled gradient region consists of one or more wafer thin booster heaters, an adjustable length adiabatic zone, and a controllable heat sink. The booster heaters and the use of a heat transfer medium between the sample and the heating module provide much steeper thermal gradients than conventional Bridgman furnaces in the solidification region. The furnace thereby allows stabilization of the interface against constitutional breakdown.

OPERATIONAL PARAMETERS

Power	500 watts max
Voltage	28 ±4 vdc
Cold zone operating range	ambient to 600°C
Hot zone operating range	ambient to 1000°C
Booster heater range	ambient to 1400°C
Thermal gradient*	0 to 900°C
Translation rate	1.0 to 50 mm/hr

SAMPLE PARAMETERS

Capacity	two samples/flight
Ampoule outer diameter	3.5 cm max.
Ampoule length	25.0 cm

PHYSICAL CHARACTERISTICS

Overall dimensions:	
Diameter	17.8 cm
Length	56.0 cm
Weight	approx. 68 kg

INTEGRAL INSTRUMENTATION A motion control programmer for sample positioning and control, and an AADSF controller for CPU, power electronics, and housekeeping will be provided.

DATA ACQUISITION CAPABILITIES Temperature at various control points vs. time, temperature rate vs. time.

FACILITY INTEGRATION OPTIONS Each AADSF will be housed in an Experiment Apparatus Container (EAC) and mounted on the Material Science Lab (MSL) in the Orbiter Payload Bay.

ADDITIONAL NOTES

*Dependent on sample material

An engineering prototype has been completed; first flight is planned for 1986.

Further information may be obtained from James A. Fountain/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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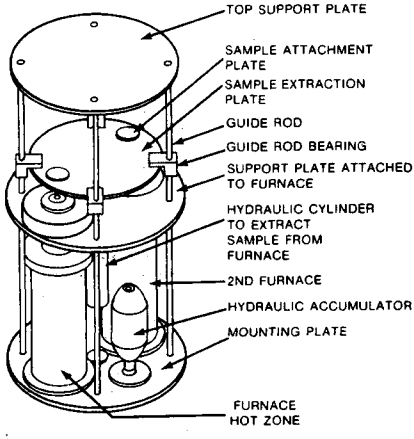
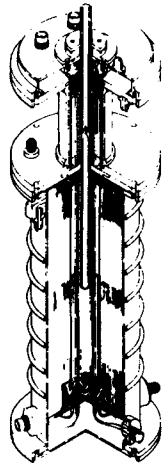
ADVANCED AUTOMATED DIRECTIONAL SOLIDIFICATION FURNACE

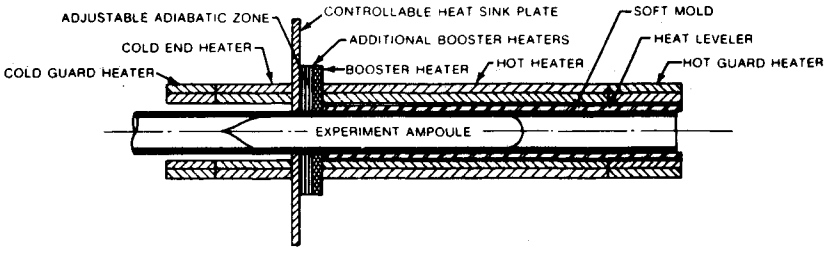
APPARATUS



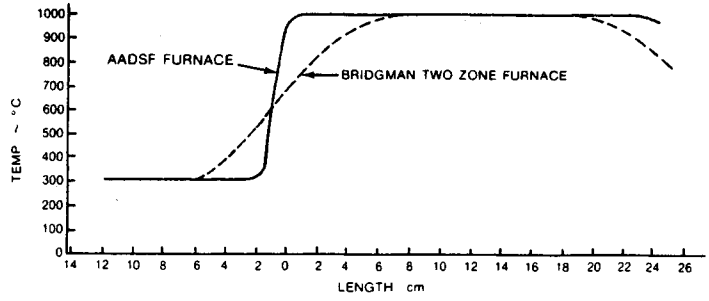
FURNACE MODULE



FURNACE SECTION



TEMPERATURE PROFILE



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STATIC COLUMN ELECTROPHORETIC SEPARATOR

EXPERIMENTAL CAPABILITY Up to eight column assemblies can be operated and photographed in each apparatus. A constant voltage (nominally 70 vdc) power supply in the apparatus is used to apply potential to a maximum of eight columns. The output of the 70 vdc power supply is 40 ma. Once the apparatus is manually turned on, it operates for 90 minutes and then shuts itself off. During the 90 minutes of operation, 35 mm photographs are taken once every three minutes for the first 10 frames, and then once every two minutes for 30 frames. This photography sequence can be changed by changing the time-and-control printed circuit board assembly. Columns which require no power can be flown without modification of the apparatus. The multi-output power supply would have to be modified to provide different column voltage and/or current.

The meter printed circuit board assembly has nine light emitting diodes (LED) on it that are turned on when each photograph is taken. One LED displays the potential applied to all columns, and the remaining eight displays the current passing through each column.

MODE OF OPERATION Each column contains a mixture of a buffer solution and ampholytes to be separated. Once the 70 vdc is applied to each column assembly, the buffer establishes a pH gradient. Each ampholyte to be separated has its own pH. It migrates to the point in the buffer solution where it and the solution have the same pH, which is known as its isoelectric point (pI).

OPERATIONAL PARAMETERS

Voltage	115 vac
Power	32 watts

SAMPLE PARAMETERS

Capacity	8 samples
Sample container length	15 cm
diameter	0.477 cm

PHYSICAL CHARACTERISTICS

Apparatus length	34 cm
width	17.5 cm
height	12.5 cm
weight	3.4 kg

INTEGRAL INSTRUMENTATION Voltage and temperature readouts are provided with high quality photographic recording.

DATA ACQUISITION CAPABILITIES Sample behavior, voltage, column temperature, and time are photographically recorded.

FACILITY INTEGRATION OPTIONS The apparatus is intended for use on the Orbiter middeck.

ADDITIONAL NOTES The presently available apparatus requires refurbishment and modifications to suit specific experiments.

Further information may be obtained from Kenneth R. Taylor/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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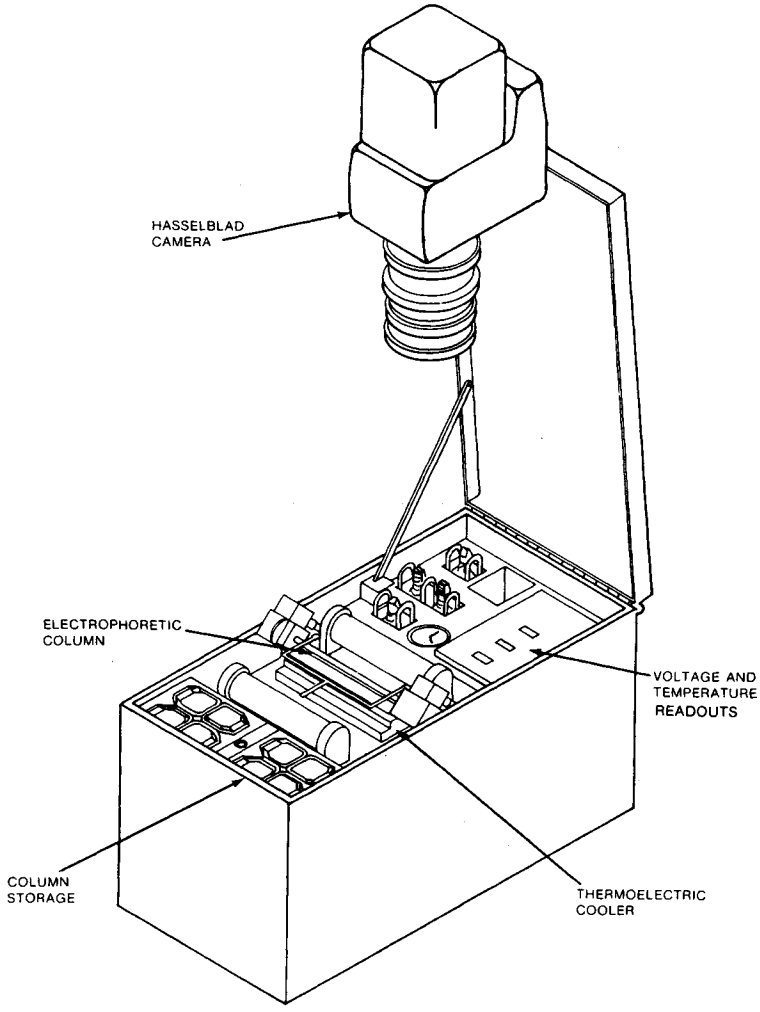
STATIC COLUMN ELECTROPHORETIC SEPARATOR



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CONTINUOUS FLOW ELECTROPHORESIS SYSTEM

EXPERIMENTAL CAPABILITY This system has been developed to permit exploratory separations of biological materials. The cell handling facilities allow the separation of living cells as well as macromolecules. A large cross section chamber permits a high continuous rate of flow, consequently increasing the potential process volume of the sample material. Sample temperature can be maintained for several hours, permitting the recovery of living cells.

MODE OF OPERATION The sample is injected into the electrophoresis chamber and carried into an electric field by the buffer. Under the influence of the field, in microgravity, the various subfractions of the sample are deflected according to their respective mobilities and enter a channel collector at the end of the chamber. Ideally each fraction segregates into a different channel where it is then moved through tubing by a peristaltic pump to collection bags in a thermally controlled chamber.

OPERATIONAL PARAMETERS

CFES Input Voltage	28 ± 4 vdc
CFES Input Power, Maximum	600 watts

SAMPLE PARAMETERS The apparatus is capable of multiple sample operation. In addition a small thermoelectric refrigerator is provided for storage material before and after processing.

PHYSICAL CHARACTERISTICS (Fluid Systems Module)

height	183 cm
width	61 cm
depth	46 cm
weight (Block III, entire system)	376 kg

INTEGRAL INSTRUMENTATION Microcomputer for experimental control and monitoring is included.

DATA ACQUISITION Data analysis is performed on the finished product. A Nikon F-2 camera is available to obtain process photographs.

FACILITY INTEGRATION OPTIONS The experiment control and monitoring module, and the sample storage module are located in middeck lockers, while the fluid systems module is mounted adjacently in the middeck.

ADDITIONAL NOTES Further information may be obtained from James T. Rose, McDonnell Douglas Astronautics Co., P. O. Box 516, St. Louis, MO 63166.

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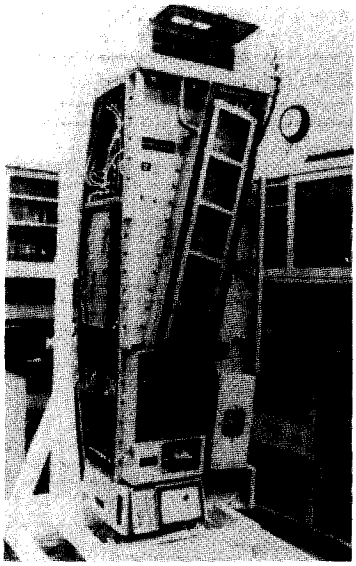
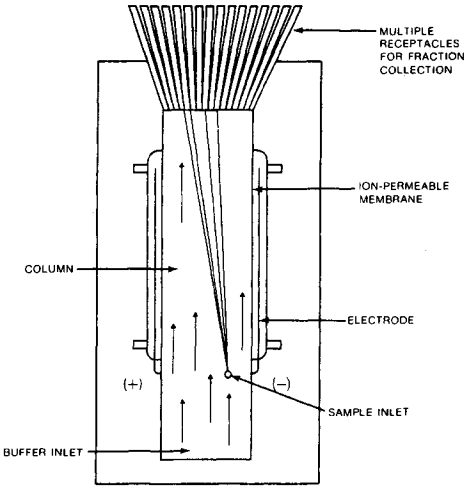
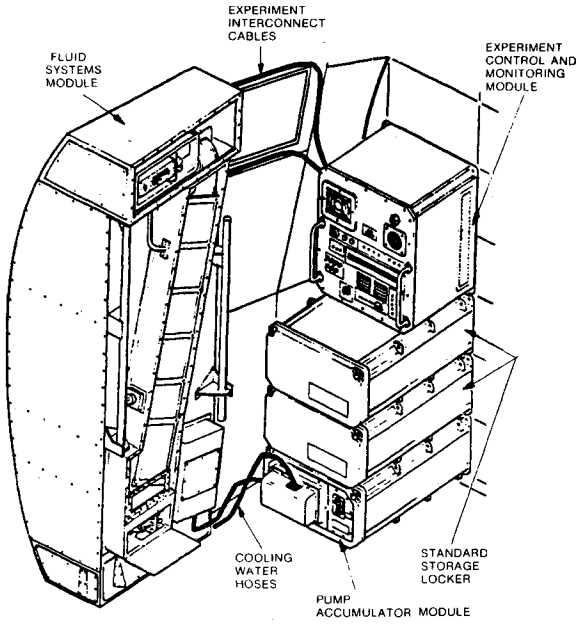
CONTINUOUS FLOW ELECTROPHORESIS SYSTEM



ELECTROPHORESIS PROCESS



ORBITER MIDDECK EQUIPMENT ARRANGEMENT (BLOCK III)



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ISOELECTRIC FOCUSING EXPERIMENT

EXPERIMENTAL CAPABILITY This apparatus was developed to determine the best isoelectric column configuration for a recycling isoelectric focusing (RIEF) apparatus designed for operation in low-g. Ground-based RIEF is possible only through the use of screen elements which assure laminarity of flow by minimizing electroosmosis and limiting convection. The isoelectric focusing experiment (IEF) contains eight column assemblies. The first use of the apparatus had columns with different combinations of three kinds of partitions, two kinds of buffers, and one kind of antielectroosmosis coating.

MODE OF OPERATION Seventy volts direct current is simultaneously applied across (end-to-end) each column to produce a pH gradient in the buffer and focusing of the materials to be separated. Movement of the colored samples to their isoelectric points (the point where the pH of the sample and the pH of the buffer are the same) is recorded photographically.

OPERATIONAL PARAMETERS

Constant voltage to each column ..... 70 vdc
Total current limited to ..... 40 ma

SAMPLE PARAMETERS

Sample capacity ..... 8 column assemblies

PHYSICAL CHARACTERISTICS The apparatus is configured to replace a standard middeck storage locker.

INTEGRAL INSTRUMENTATION LED display of voltage and current is turned on for each photograph.

DATA ACQUISITION CAPABILITIES Forty 35mm photographs, first 10 taken at 3 minute intervals, remaining 30 taken at 2-minute intervals.

FACILITY INTEGRATION OPTIONS The apparatus is designed to mate with a single adaptor plate in the Orbiter middeck.

ADDITIONAL NOTES Further information may be obtained from Kenneth R. Taylor/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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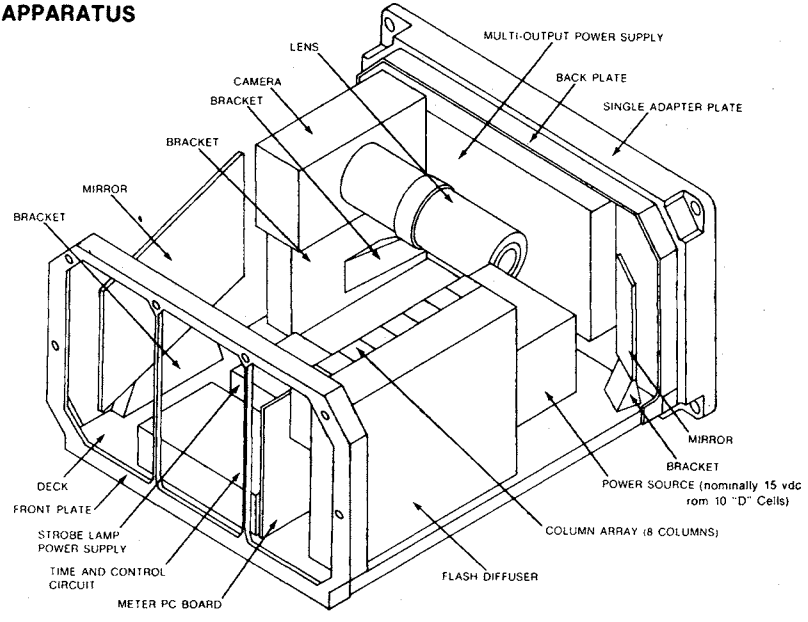
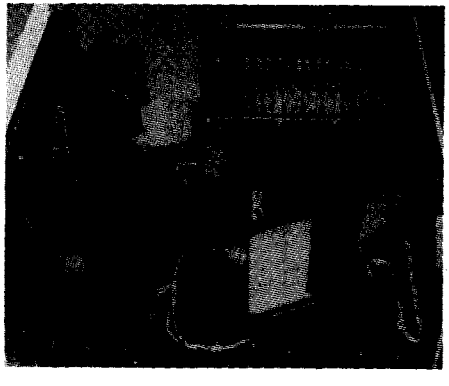
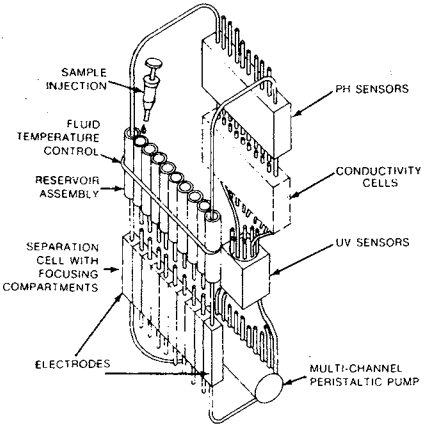
ISOELECTRIC FOCUSING EXPERIMENT

APPARATUS





PLANNED RECIRCULATING IEF SYSTEM



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SINGLE AXIS ACOUSTIC LEVITATOR

EXPERIMENTAL CAPABILITY The Single Axis Acoustic Levitator (SAAL) is a containerless processing facility using an interference technique to automatically adjust for changes in the speed of sound as the temperature changes. Samples are injected into a hot-wall furnace that can be heated up to 1600°C in an atmospheric environment. After melting, the sample is solidified by allowing it to radiate into an acoustically transparent heat sink. Additional samples may be processed sequentially. The specimen can be positioned without physical means by a weak acoustic levitator and operated automatically following activation. The apparatus is useful for studying the containerless formation of glasses, ceramics, or other materials that require the presence of an inert atmosphere.

MODE OF OPERATION The sample is positioned in the acoustic energy node formed by the interference of the incident sound wave with the wave reflected from a small reflector inserted into the insulated chamber with the sample. Four silicon carbide heating rods surround the levitated sample during the melt phase, and an array of stainless steel rods are inserted into the heating cavity to allow radiative cooling and solidification. The solidified sample is then retrieved by a retracting cage and another sample automatically inserted. A quartz window serves as a port for photography of the specimen during the processing sequence.

OPERATIONAL PARAMETERS

Operating temperature	up to 1600°C
Voltage	32 vdc
Power (peak/average)	3100/2600 watts
Pressure	1 atm
Atmosphere	air or inert gas
Levitator frequency	15-20 kHz
Cooling rate*	15°C/sec

SAMPLE PARAMETERS

Capacity	up to 8 samples
Spherical diameter	up to 1.5 cm

PHYSICAL CHARACTERISTICS

Furnace length	71cm
Furnace diameter	43 cm
Furnace weight	61.3 kg
Processing chamber	10.2 x 10.2 x 11.4 cm
Injector cage	2.5 x 2.5 x 2.85 cm

INTERGRAL INSTRUMENTATION A pyrometer records sample temperature while a movie camera provides a photographic record of the process sequence.

DATA ACQUISITION CAPABILITIES Temperature and photographic record.

FACILITY INTEGRATION OPTIONS Operation of this apparatus is restricted to the Materials Experiment Assembly located in the Orbiter payload bay.

ADDITIONAL NOTES The SAAL flew as part of MEA-A1 on STS-7, June, 1983.
*Sample dependent
Further information may be obtained from Harry L. Atkins/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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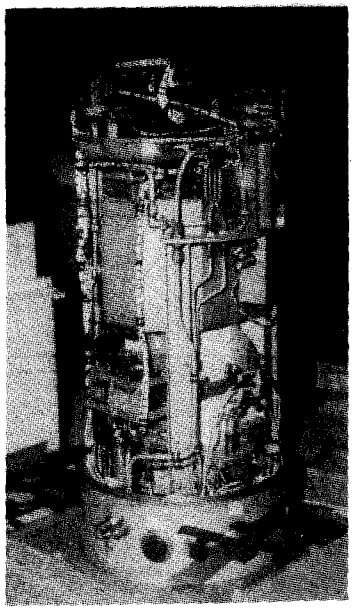
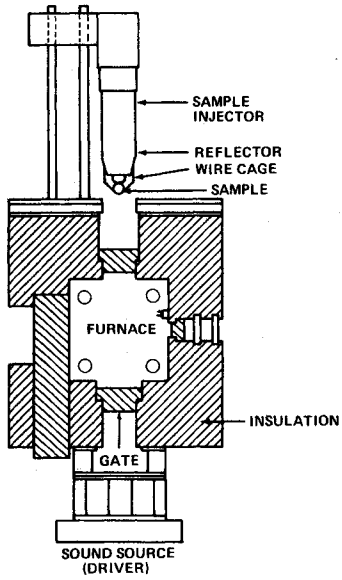
SINGLE AXIS ACOUSTIC LEVITATOR





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THREE AXIS ACOUSTIC LEVITATOR

EXPERIMENTAL CAPABILITY This Three Axis Acoustic Levitator (3AAL) apparatus permits a liquid specimen to be positioned and manipulated by a three-dimensional acoustic energy well. Manipulations include rotation, oscillation and drop fusion/fission. The oscillation and rotation can be used to stir the liquid as well as center gas bubbles in the liquid drop. Multiple samples can be injected and controlled while color or black and white motion pictures are obtained, which provide one direct view and two reflected views on orthogonal axes. Temperature, acoustic pressure and driver power can be monitored. The apparatus permits the investigation of a variety of fluid dynamic properties and particle interactions.

MODE OF OPERATION Three acoustic drivers positioned along orthogonal axes are used to suspend the droplet in an acoustical energy wall. Pulsing or phasing of the drivers permits controlled oscillation or rotation. An injector deploys the liquid sample into the containment area with low velocity and little circulation within the liquid. The primary data recorder is a 16mm movie camera which employs a mirror system to obtain a three view record. Synchronized strobe lights allow the investigator to obtain either a color or a black and white rendition of the experimental sequence.

OPERATIONAL PARAMETERS

Voltage	28 vdc
Power	126 watts
Acoustic pressure	150 dB max
Disturbance acceleration tolerance	10^{-4}g
Estimated acoustic pressure (fundamental mode)	1 dyne/cm^2

SAMPLE PARAMETERS

Sample diameter	0.3-2.5 cm
Sample volume	0.14-8.0 cm^3
Max. sample translation	3 cm
Max. sample rotation	30 rps

PHYSICAL CHARACTERISTICS

Apparatus length	68.58 cm
Apparatus diameter	38.74 cm
Apparatus weight	70.82 kg
Chamber size	11.5 x 11.5 x 12.7 cm

INTEGRAL INSTRUMENTATION Drop positioning sensors (2) and a 16 mm video camera with a mirror system.

DATA ACQUISITION CAPABILITIES Color or black and white three view video record of the processing sequence.

FACILITY INTEGRATION OPTIONS The apparatus is housed in an Experiment Apparatus Container and mounted in the Orbiter payload bay.

ADDITIONAL NOTES Further information may be obtained from Charles L. Youngberg, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109.

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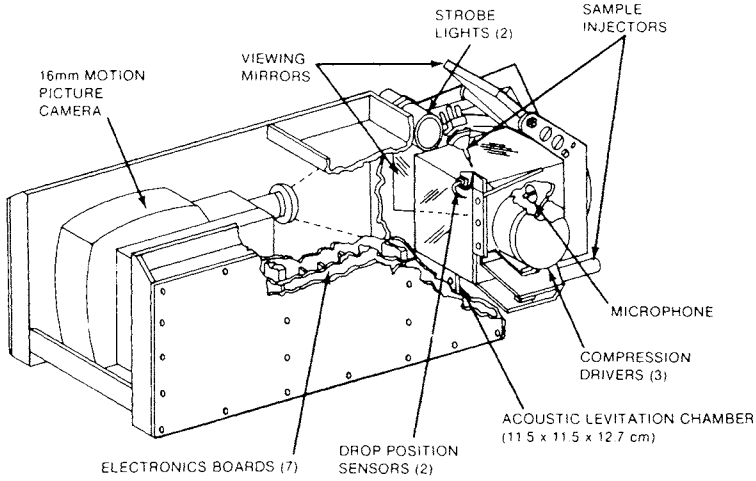
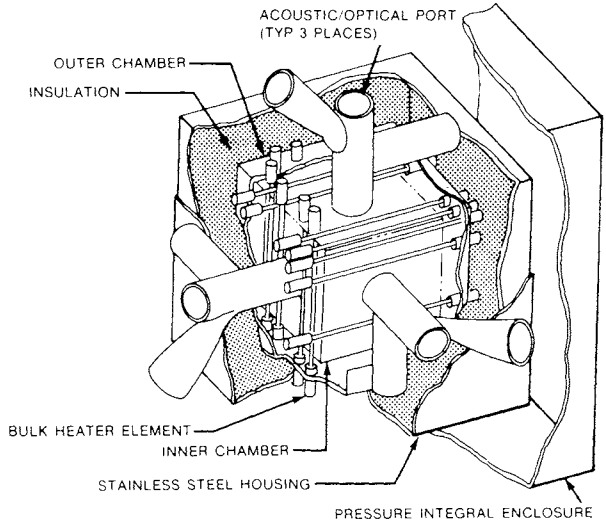
THREE AXIS ACOUSTIC LEVITATOR

ACOUSTIC LEVITATION SYSTEM



LEVITATION CHAMBER



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ACOUSTIC CONTAINERLESS EXPERIMENT SYSTEM

EXPERIMENT CAPABILITY The Acoustic Containerless Experiment System (ACES) is a flight facility that will melt and acoustically oscillate a single sample of glass, ceramic, or metal while it is acoustically restrained within the central area of a resistance heated rectangular furnace filled with an inert gas. The experiment is monitored by thermal sensors and a video recording system during the 120 minute duration which provides about 15 minutes at the present limitation of 620°C.

MODE OF OPERATION The furnace is an insulated resistance heated Inconel chamber of 6.3 by 6.3 by 7.0 cm internal dimensions. The energy of three acoustic drivers enters the chamber through three orthogonal ports and forms resonant standing waves within the chamber to restrain sample excursions from the effects of external g perturbations.
Resonant frequency is tracked through the chamber temperature changes and adjusted to maintain resonance and sample location control. Rotation and oscillation of the sample can be programmed into the experiment.

OPERATIONAL PARAMETERS (FLIGHT ON STS-41B)

Voltage	28 vdc
Power	160 watts
Operating temperature	620°C (900°C potential)
Heating rate	10°C/min.
Cooling rate	4.5°C/min.
Furnace gas environment	dry nitrogen at 14.7 psi
Electronics gas environment	30% humidity nitrogen/10% helium

SAMPLE PARAMETERS

Sample capacity	1 sample/flight
Sample size	approximately 1.0 cm diameter

PHYSICAL CHARACTERISTICS

Two cannisters:	inside diameter 42.16 cm
	inside length 44.07 cm

INTEGRAL INSTRUMENTATION Single axis video system, add-on micro-accelerometer externally mounted.

DATA ACQUISITION CAPABILITIES Data for temperature, electrical, and acoustic performance recorded on audio portion of videotape.

FACILITY INTEGRATION OPTIONS This unit was located in the forward locker array of the Orbiter on flight STS-41B.

ADDITIONAL NOTES The ACES has been ground tested and flown on STS-41B. Post-flight modifications are now progressing.
Further information may be obtained from Charles L. Youngberg, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109.

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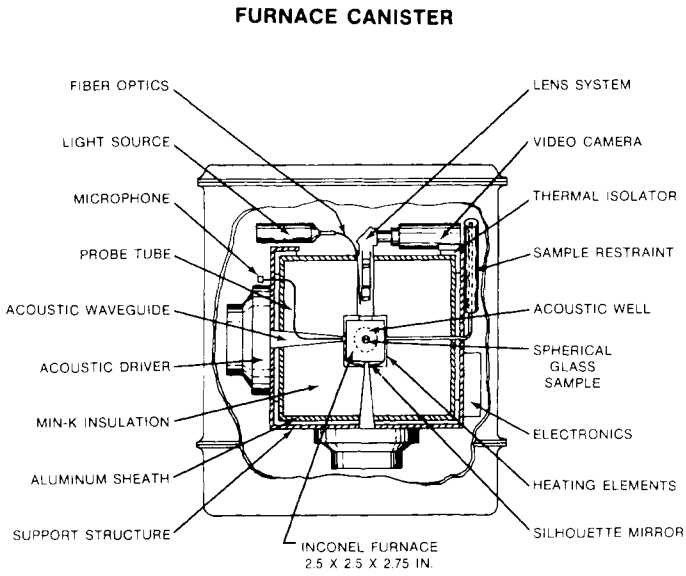
ACOUSTIC CONTAINERLESS EXPERIMENT SYSTEM



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ELECTROMAGNETIC LEVITATOR FURNACE

EXPERIMENTAL CAPABILITY The Electromagnetic Levitator Furnace (EML) allows a conductive sample to be positioned in the levitation coil and melted by inductive heating in a vacuum or controlled gaseous environment. Following the melt phase, power may be reduced at a rapid rate, allowing radiative cooling and solidification of the specimen. Additional cooling is possible through the use of a quench gas. Pyrometric observation of the specimen surface, without interference from a container wall, can also be accomplished. The apparatus is useful for performing undercooling and nucleation studies, preparation of amorphous and metastable phases in metallic systems, and thermophysical measurements.

MODE OF OPERATION The sample is suspended in the electromagnetic field of a cusp coil and is heated and melted by induction from the coil's electromagnetic field. The cusp coil consists of adjacent coils having opposing alternating magnetic fields. An active servo positioning system maintains the electrically conductive specimen in the center of the coil system against acceleration during flight and damps oscillations of the specimen. The experimental sequence is controlled by a timer allowing fully automatic operation following initiation of the timer sequence.

OPERATIONAL PARAMETERS

Voltage	28 vdc
Power	1204 watts
Operating temperature*	1300°C

SAMPLE PARAMETERS

Capacity	6 samples
Spherical diameter	0.9 cm

PHYSICAL CHARACTERISTICS

Furnace length	58.4 cm
Furnace diameter	35.6 cm
Furnace weight	42.0 kg

INTEGRAL INSTRUMENTATION Pressure and temperature sensors, pyrometer, timer, and 16 mm motion picture camera.

DATA ACQUISITION CAPABILITIES Heating, melting, and solidification sequence recorded photographically; temperature data recorded by solid state silicon detector.

FACILITY INTEGRATION OPTIONS Operation of this apparatus is restricted to the Materials Science Lab located in the Orbiter payload bay.

ADDITIONAL NOTES

*Actual temperature achieved is a function of sample size, emissivity, and resistivity.
Further information may be obtained from Harry L. Atkins/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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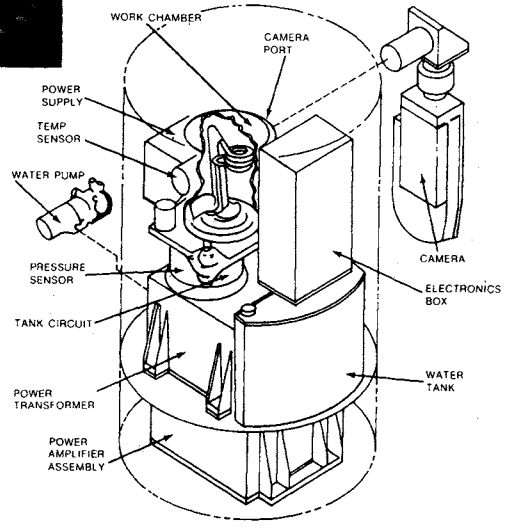
ELECTROMAGNETIC LEVITATOR FURNACE



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FLUIDS EXPERIMENT SYSTEM

EXPERIMENTAL CAPABILITY The Fluids Experiment System (FES) is a multi-purpose fluids research facility used to investigate crystal growth phenomena in microgravity through utilization of the grown crystal and holographic records of the growth process. It can accommodate a variety of experimental cells for performing a broad range of fluid experiments in areas such as fluid convection, phase transition, surface physics, and bubble behavior. Samples can be processed for post-flight anaylsis, and real time flow visualization can be obtained using a schlieren technique. The facility will allow confirmation of the advantages of microgravity environment and evaluation of the feasibility of producing solution grown crystals on orbit.

MODE OF OPERATION The system includes an optical bench for making holograms of a test cell from two orthogonal views. Real time viewing in schlieren or shadowgraph modes is provided by means of a video system. The test cell being flown on SL-3 is designed for solution crystal growth using a cooled sting to control the degree of saturation at the growth interface. Composition profiles can be mapped using holographic interferometry. The system is designed to be used in combination with the Vapor Crystal Growth System (VCGS) and, as such, provides support to the VCGS for microprocessor control, and data acquisition, display and transmission.

OPERATIONAL PARAMETERS

Holographic resolution	<20u @ 10:1 contrast ratio
Holographic capacity	450 photos each, transverse and primary
Heating/cooling rate	0.5°C/min
Operating temperature of test cell	ambient to 70°C (SL-3 only)
Power	1.0 kw max average
Cooling	10-20°C Water, 10-35°C Air

SAMPLE PARAMETERS (Spacelab III Mission)

Crystal isolation	<8°C/cm gradient
Residual fluid	2.0 cc
Crystal growth duration	2 test cells @ 24 hrs 1 test cell @ 60 hrs
Test cell fluid	triglycine sulfate 1.8-2.5 pH

PHYSICAL CHARACTERISTICS The FES is configured within a Spacelab double rack.

INTEGRAL INSTRUMENTATION Closed circuit television with remote to ground, 70 mm holographic recorder, accelerometer, and Process Control and Data Acquisition (PCDA) microprocessor.

DATA ACQUISITION CAPABILITIES PCDA microprocessor provides all data processing requirements (up to 1 sps/parameter) and transmits directly to the Spacelab high rate multiplexer for ground link.

FACILITY INTEGRATION OPTIONS The system is designed for installation in a Spacelab double rack.

ADDITIONAL NOTES The FES and VCGS Systems have demonstrated satisfactory performance in a 1g environment, and are currently scheduled for first flight on Spacelab 3 Mission 51-B in early 1985.
Further information may be obtained from Leonard Yarbrough/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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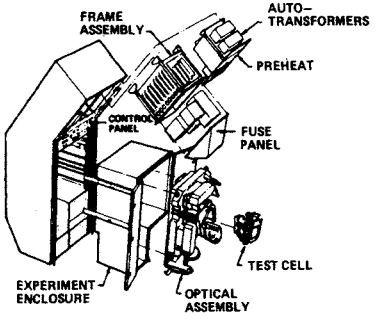
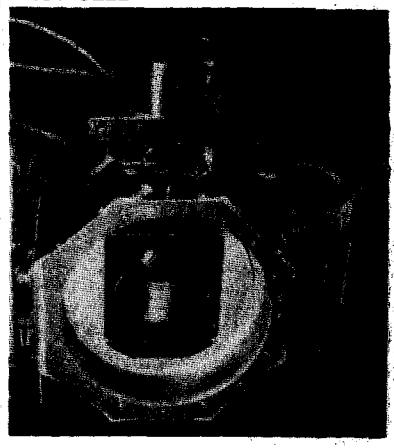
FLUIDS EXPERIMENT SYSTEM

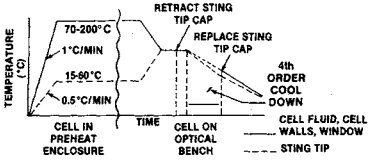
EXPLODED VIEW



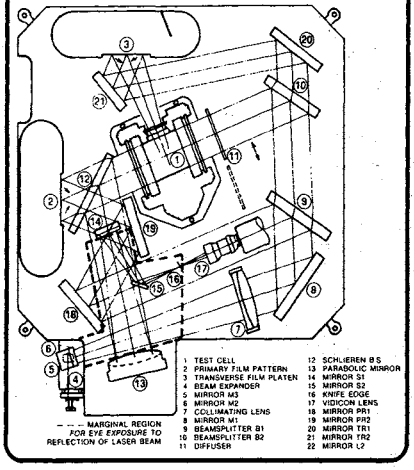
TEST CELL



TEMPERATURE PROFILE (SL-3)



HOLOGRAPHIC VIDEO SYSTEM



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FLUID EXPERIMENT APPARATUS

EXPERIMENTAL CAPABILITY The Fluid Experiment Apparatus (FEA) is a modular microgravity chemistry/physics experiment system to support fundamental space processing research. It is designed to conduct basic and applied process or product development experiments in general liquid chemistry, crystal growth, fluid mechanics, thermodynamics, cell culturing, and additional areas.

MODE OF OPERATION A number of specialized subsystems are planned for the FEA. These modules will allow the FEA to be configured to support a wide range of experimental requirements. The current configuration (FEA-1) will accommodate float zone crystal growth and certain fluid handling experiments. The mode of operation will vary greatly dependent upon specific experiment requirements.

OPERATIONAL PARAMETERS To be determined by specific experiment requirements.

SAMPLE PARAMETERS To be determined by specific experiment requirements.

PHYSICAL CHARACTERISTICS The FEA is completely self-contained and configured to replace a standard Orbiter middeck storage locker.

INTEGRAL INSTRUMENTATION To be determined by specific experiment requirements.

DATA ACQUISITION CAPABILITIES A variable frame rate (1/60 to 36 seconds) photographic recording system is included. Additional data acquisition capabilities can be provided.

FACILITY INTEGRATION OPTIONS The unit will be mounted in place of middeck storage locker.

ADDITIONAL NOTES The FEA has been developed by Rockwell International and is currently available for flight.
Further information may be obtained from Michael J. Martin, Rockwell International, 12214 Lakewood Blvd., Downey, CA 90241.

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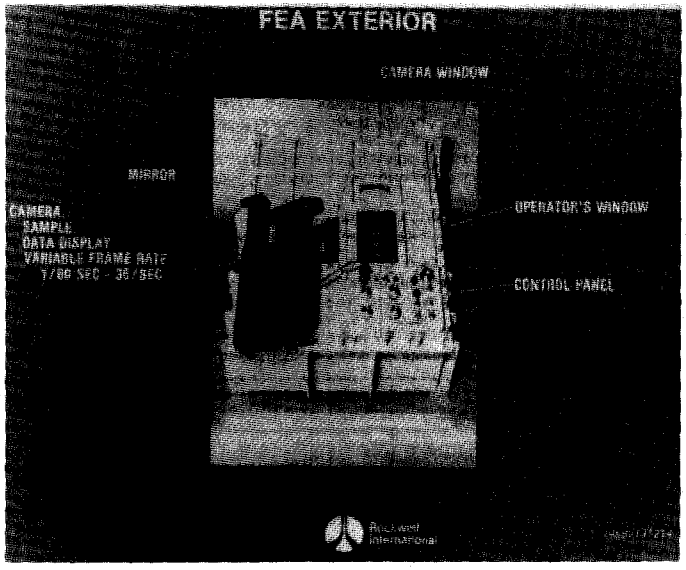
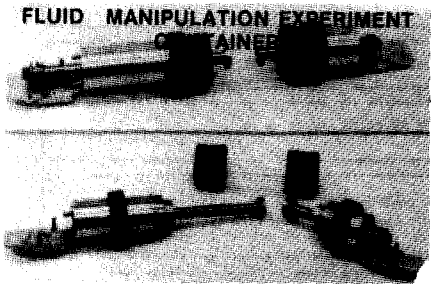
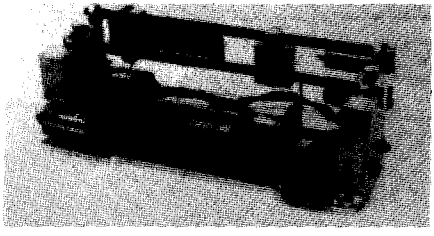
FLUID EXPERIMENT APPARATUS



FLUID MANIPULATION EXPERIMENT CHAMBER



EXPERIMENT MANIPULATION ASSEMBLY



FLUID STORAGE AND PUMPING ASSEMBLY

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VAPOR CRYSTAL GROWTH SYSTEM

EXPERIMENTAL CAPABILITY The Vapor Crystal Growth System (VCGS) is a special purpose facility emulating vapor crystal growth ground experimentation hardware, providing both the grown crystal and in-flight microscopic observation of the growth process via closed circuit television. The apparatus is useful in comparing the structural and spectrographic properties of microgravity grown crystals with Earth grown crystals to determine low-g growth effects. It meets the objective of growing single crystals by vapor transport while inhibiting polycrystalline nucleation.

MODE OF OPERATION The VCGS furnace contains three separate heating elements. The growth ampoule contains a temperature controlled pedestal which positions and controls the seed temperature. Source material for the vapor transport process is positioned on the ampoule sidewall. A binocular microscope is used by the Payload Specialist to monitor the growth process and modify the growth parameters as required. The VCGS is designed to be used in conjunction with the Fluids Experiment System (FES) and relies on the FES for support in the areas of data entry/display, process control, and power control/distribution.

OPERATIONAL PARAMETERS

Source heater range	100-120°C
Source heater modulation	±2.5°C
Source heater rate	5°C per 2 min
Ring heater range	120-180°C
Ring heater rate	0.005-0.500°C per hr
Sting heater range	40-80°C

SAMPLE PARAMETERS

Test ampoule diameter	8.0 cm
Test ampoule length	11.0 cm
Test ampoule strength	1.5 atm @ 180°C
Test chamber air loop	20-30°C ±1°C

PHYSICAL CHARACTERISTICS The VCGS is configured within a Spacelab single rack.

INTEGRAL INSTRUMENTATION 10-30x microscope, closed circuit television, and PCDA microprocessor when used in conjunction with FES.

DATA ACQUISITION CAPABILITIES When used in conjunction with FES, and the FES PCDA microprocessor handles all data processsing requirements and transmits directly to the Spacelab high rate multiplexer for ground link.

FACILITY INTEGRATION OPTIONS The VCGS is designed for installation in a Spacelab single rack located adjacent to the FES facility.

ADDITIONAL NOTES The VCGS has demonstrated satisfactory performance in a 1g environment and is currently scheduled for first flight on Spacelab 3 Mission 51-B in early 1985.
Further information may be obtained from Leonard Yarbrough/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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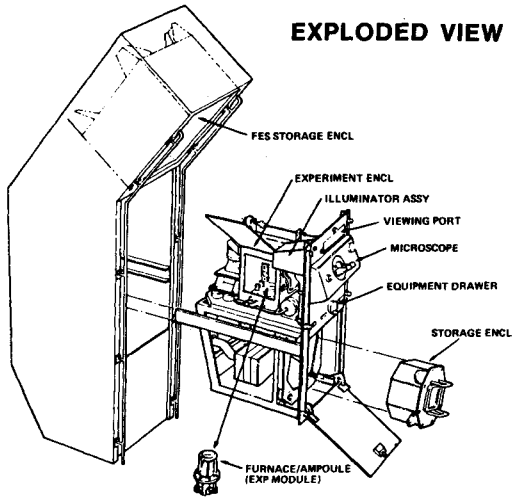
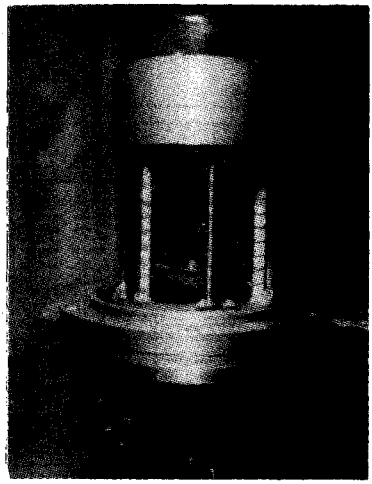
VAPOR CRYSTAL GROWTH SYSTEM

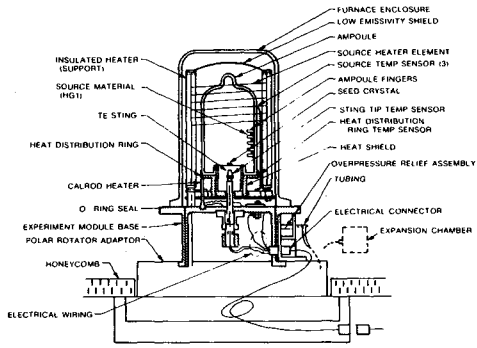
EXPLODED VIEW



VCGS RACK ASSEMBLY



FURNACE/AMPOULE ASSEMBLY



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MONODISPERSE LATEX REACTOR SYSTEM

EXPERIMENTAL CAPABILITY The Monodisperse Latex Reactor System (MLRS) consists of four reactors in an Experiment Apparatus Container (EAC), a Support Electronics Package (SEP), and two interconnecting cables, one for power and the other for signal.

MODE OF OPERATION Up to four 100 ml batches of material can be stirred only in the preprocess mode, or stirred and heated in the process mode. Two temperatures are available, nominally 70 to 90°C. During the process mode, one volume and four temperatures (base, wall, piston, and fluid) are measured. The SEP converts this analog data to digital data and records it once every minute.

OPERATIONAL PARAMETERS

SEP input voltage	28 ± 4 vdc
MLR input voltage	36 vdc
SEP input current	13 amp (max)
MLR input current	6 amp (max)

SAMPLE PARAMETERS

Capacity	4 samples
Sample volume	100 ml
Cylinder inner diameter	4.1 cm.
Cylinder length	7.8 cm.

PHYSICAL CHARACTERISTICS

Reactor length	38.1 cm.
Reactor diameter	20.6 cm.
Reactor weight	6.8 kg.

INTEGRAL INSTRUMENTATION Volume change (1), temperature probes (4)

DATA ACQUISITION CAPABILITES The SEP can record up to 22 channels of data at a rate of 1 sps.

FACILITY INTEGRATION OPTIONS The MLR is designed to be housed in an experiment apparatus container (EAC)and attaches to a double adaptor plate in the Orbiter middeck.

ADDITIONAL NOTES The MLR has been flown on five missions and is currently scheduled for three more missions.
Further information may be obtained from James A. Fountain/PS05, Commercialization of Materials Processing in Space Group, Marshall Space Flight Center, AL 35812.

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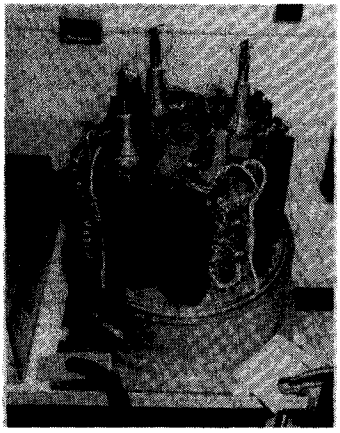
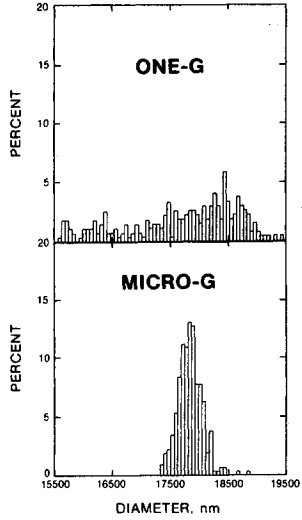
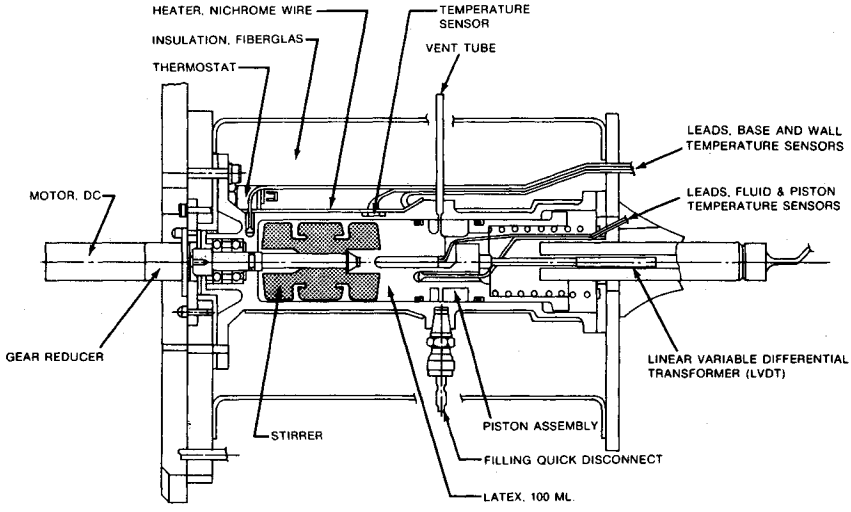
MONODISPERSE LATEX REACTOR SYSTEM



TYPICAL PARTICLE SIZE DISTRIBUTION



FULL SECTION OF ONE REACTOR



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SOLUTE DIFFUSION APPARATUS*

EXPERIMENTAL CAPABILITIES The Solute Diffusion Apparatus can keep liquid reactant solutions separated until established in earth orbit, and then open the valves separating them to allow the solutions to diffuse together slowly and react chemically to form single crystals without gravitational effects. The apparatus can control and record the temperature of the solutions and provide for their thermal expansion or contraction. The solution volumes are variable.

MODE OF OPERATION The apparatus consists of four cylindrical reactors surrounded by a cylindrical resistance heater in an insulated cylindrical enclosure and a microcomputer in a separate cylindrical enclosure. Each reactor has three compartments. The two outer compartments contain the reactant solutions and are separated by a central compartment containing pure solvent. The three compartments are separated by valves designed to cause virtually no stirring when they are opened. The microcomputer controls the entire process, including control and recording of the temperature and opening of the valves. Electric power is supplied by batteries.

OPERATIONAL PARAMETERS

Operating temperature	260-320°K
Power consumption	5 watts
Maximum power	37.5 watts

SAMPLE PARAMETERS

Total volume per reactor	2 liters

PHYSICAL CHARACTERISTICS

Reactor outside diameter	7.6 cm
Reactor length	71 cm
Reactor enclosure outside diameter	30 cm
Reactor enclosure length	82 cm
Reactors and enclosure mass	48.6 kg
Microcomputer outside diameter	21 cm
Microcomputer length	28 cm
Microcomputer mass	8.5 kg

INTEGRAL INSTRUMENTATION *Thermistors with microcomputer control.*

DATA ACQUISITION CAPABILITIES Reactor temperature is recorded at regular intervals in microcomputer random access memory.

FACILITY INTEGRATION OPTIONS Apparatus may be located in Orbiter payload bay, middeck, or free-flying retrievable satellite.

ADDITIONAL NOTES The Solute Diffusion Apparatus has been designed and developed by Rockwell International Defense Electronics Operations and is currently in flight on the LDEF (1984 to early 1985). Further information may be obtained from Dr. M. David Lind, Rockwell International, 1049 Camino Dos Rios, P. O. Box 1085, Thousand Oaks, CA 91360.

*** Illustration for the Solute Diffusion Apparatus is not available.**

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